Artificial Recharge of Groundwater in the World

Report

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1 CONTEXT

1.1 Introduction

The provision of fresh water for domestic or agricultural purposes is not only concerned with the spatial availability of water but has also a time dimension. On an annual basis, there should be enough water available to supply the spatial water demands, but the fluctuations throughout the year are equally important to secure the provision of water to consumers when it is needed. Storage is the key word to smoothen out the gaps between water availability and consumers demand. Besides the short term (overnight) storage in reservoirs to balance daily demand fluctuations, the longer term (weekly and longer) storage is provided by surface storage in reservoirs or by groundwater storage. Table 1 (Seckler, 2000) gives some key characteristics of groundwater storage and surface water storage:

Table 1. Characteristics of groundwater storage and dam storage.

	Groundwater storage	Small dams and surface reservoirs	Large dam reservoirs
Advantages	Little evaporation Widely distributed Operational efficiency Available on demand Water quality	Ease of operation Response to rainfall Multiple use Groundwater recharge	Large, reliable yield Carryover capacity Low cost per m^3 water stored Multi purpose (power & flood control) Groundwater recharge
Limitations	Slow recharge rate Groundwater contamination Cost of extraction Recoverable fraction	High evaporation losses Relatively high unit cost Absence of over-year storage	Complexity of operation Siting High initial investment cost Time needed to plan & construct
Key issues	Declining water levels Rising water levels Management of acces/use Groundwater salinization Groundwater pollution	Sedimentation Adequate design Dam safety Environmental impacts	Social impacts Environmental impacts Sedimentation Dam safety

Source: IWMI Research Report no.39: Water Scarcity and the Role of Storage in Development

Groundwater storage, either naturally or artificially is an important component of the water supply chain and an important alternative for surface water storage behind dams (Tuinhof, 2003). Managed Aquifer Recharge (MAR) can be used in conjunction with water harvesting techniques to recharge an aquifer by catching water during rainfall, thus impeding the quick runoff out of a catchment area. Aquifers can provide a store of water, which, if utilised and managed effectively, can play a vital role (Gale, 2005) in:

- Poverty reduction/livelihood stability
- Risk reduction; both economic and health
- Increased agricultural yields resulting from reliable irrigation
- Increased economic returns
- Distributive equity (higher water levels mean more access for everyone)
- Reduced vulnerability (to drought, variations in precipitation)

Artificial recharge is defined as any engineered system designed to introduce and store water in an aquifer (Topper R. et al. 2004). However, an adverse connotation of 'artificial', in a society where community participation in water resources management is becoming more prevalent, has lead to a new name: Managed Aquifer Recharge (Gale, 2005), that will be used throughout this report

MAR applications are generally not stand-alone interventions as they are a component of the broader hydrological system and usually part of a larger water supply or water management system. Application of MAR should be considered in this broader framework in order to derive at the most cost effective solution.

On a larger scale, MAR can be useful for many of today's water issues and concerns. As an increasingly important tool for water managers it may be useful for re-pressurising aquifers subject to declining yields, saline intrusion or land subsidence. MAR can also play an important role as part of a package of measures to control over-abstraction and restore the groundwater balance (Gale 2005), or be applied with the purpose of maintaining or improving local ecology and environment. MAR may help to improve water quality in aquifers, and infiltrate storm runoff for both damage control and subsequent reuse in drinking or irrigation supplies.

Because water stored in the sub-surface can be used to meet domestic, agricultural, and industrial water supply demands, MAR can be compared with other, more conventional, technological options for water supply. MAR has the advantage over dams in that its economic size can range as low as 1 000 m^3/a, whereas dams with surface storage may need to be several orders of magnitude larger to become economic (Dillon, 2005). In arid areas, dams with surface storage have significant evaporation losses and may allow growth of blue-green algae that produce toxins. Desalination costs are decreasing, but desalination remains a relatively energy-intensive activity and needs a high level of technical support to maintain operations (Ministry of Water and Forestry of South Africa, 2005). Table 2 summarises key comparative issues of various water supply sources.

Table 2 Factors affecting technology choice for water supply

Method	Typical scale (m^3/a)	Limits	Relative capital costs	Relative investigation costs	Relative technical. knowledge needed	Relative regulation difficulty
Rainwater tanks	Family $10 – 10^2$	Fails in droughts	*	*	*	*
Springs	Family/village $10^3 – 10^4$	Can fail in droughts	**	*	*	*
Groundwater	Village/town $10^4 – 10^6$	Needs aquifer	***	**	**	**
MAR	Village/town $10^3 – 10^6$	Needs aquifer	****	***	***	***
Dam and treatment plant	Region $10^7 – 10^9$	Needs dam site	*****	****	***	***
Desalination	Town/region $10^3 – 10^7$	Needs power and brine discharge	*****	**	****	**

Source: Murray (2005); adapted from Dillon, 2005

1.2 The project.

In recent years there has been a rapid increase in the application of MAR around the world. Publication of knowledge and experiences regarding MAR has progressed accordingly, but a sound global overview of applications, and access to information about individual MAR projects is still not available. The project 'Artificial Recharge of Groundwater in the World' is launched to provide such a global overview and builds on an earlier initiative of the IAH-MAR Commission.

The project is implemented by the International Groundwater Resources Assessment Centre (IGRAC) and the Acacia Institute, in cooperation with the IAH-MAR Commission and UNESCO-IHP, and is carried out within the IGRAC framework.

igrac

The International Groundwater Resources Assessment Centre (IGRAC) is a non-commercial organisation facilitating and promoting world-wide exchange of groundwater knowledge to improve assessment, development and management of groundwater resources. An important part of IGRAC's services is making information on the globe's groundwater available through IGRAC's website (www.igrac.nl). The objective of this project is enhancing IGRAC's public information services with balanced documentation on artificial recharge of groundwater in the world, aiming is to improve the accessibility, dissemination and reuse of information and knowledge related to MAR.

Acacia Institute
Solutions in Groundwater

The Acacia Institute "for solutions in groundwater" is a self-supporting not-for-profit foundation established at the Vrije Universiteit Amsterdam (Faculty of Earth and Life Sciences). Acacia Institute is an independent, demand-oriented organization with an international scope. Its goal is to highlight the important role of groundwater in hydrological processes, as well as groundwater's importance and opportunities to society. Acacia also wants to accommodate the need for groundwater knowledge and to offer recommendations in those areas where the awareness of the importance of groundwater is emerging:

- lobbying in order to strengthen the position of groundwater on the political agenda, and
- providing innovative solutions for groundwater development, management, protection and use, and
- promoting knowledge exchange and communication among all the stakeholders in groundwater related issues and
- supporting governments, industries, and donor agencies in formulating policy and in managing programs.

1.3 Report structure

This report provides an overview of the work done in 2006 on the project ‘Artificial recharge of Groundwater in the World’. All results described in this report are made publicly available on the IGRAC website (www.igrac.nl).

The project ‘Artificial Recharge of Groundwater in the World’ was implemented in several stages. An overview of the project and the products resulting from the various stages is given in Figure 1.

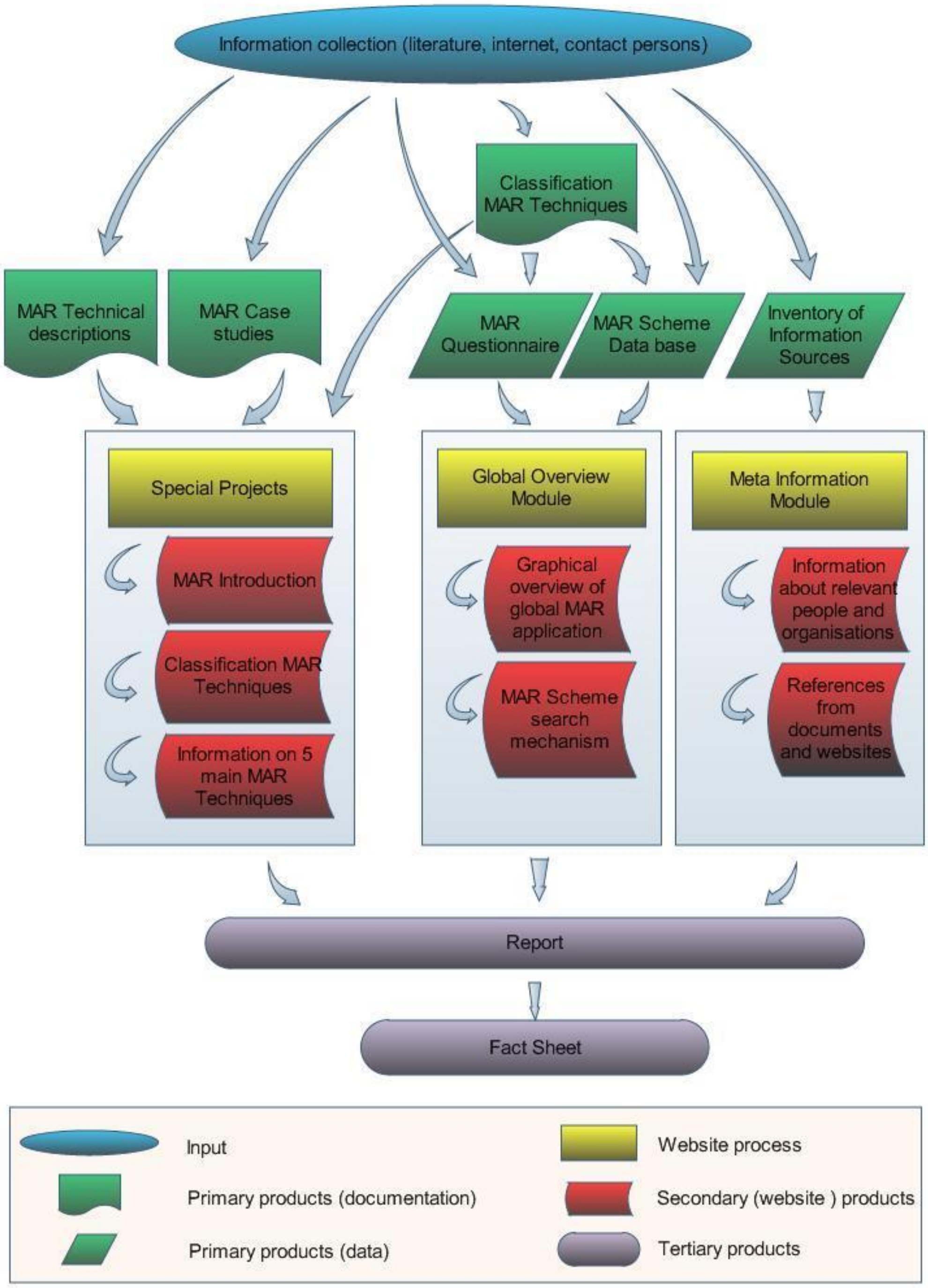

Figure 1: Flow diagram of project stages and produced outputs.

Information has been gathered through an intensive internet and library search, as well as through personal information provided by various contact persons. This information was used to create several primary products:

- **A classification of MAR techniques** gives an overview of MAR technology that is currently in use around the world. In addition it provides a necessary framework on which other outputs of this project are based (Section 2.1).
- **A MAR Questionnaire** based on the MAR classification. The questionnaire can provide regional data about MAR applications. The questionnaire has been sent to contact persons (Section 2.2, Annex 3 and 11).
- **A MAR Scheme database** to make an inventory of MAR schemes currently in operation around the world (Section 2.3).
- **An Inventory of Information sources** compiling all references of information gathered from literature and websites for this project (Section 2.4).

Information collected from literature, internet and contact persons has also been used to create several secondary products, placed in the 'special projects' section (see Annex 1) on the IGRAC website (www.igrac.nl)

- **An introduction** to provide initial insight in MAR to users of the website who are unfamiliar with the subject. Also a short description of this project is given (www.igrac.nl).
- **Technical descriptions** provide general information about the 5 main MAR techniques, and also briefly describe the sub techniques that fall into each main MAR class (Section 2.5 and Annex 7).
- **MAR Case-studies** describe some exemplary cases from the database in detail, and in doing so provide detailed information about a specific application of each main MAR technique (Section 2.6 and Annex 8).

Some primary products are used on the IGRAC website to create secondary products in the Global Overview Module and the Meta Information Module (see Annex 1).

- The MAR scheme database and response from the questionnaire returned by contact persons contain country based information about MAR applications worldwide. This information can be used in the Global Overview Module to provide a **graphical overview of MAR application in the world** (Annex 1).
- The MAR scheme database can be accessed directly on the IGRAC website through a **sophisticated case based reasoning search mechanism** providing access to detailed records on individual applications of MAR techniques (Annex 1).
- The inventory of information sources and references from the first stage products used in the Global Overview Module are added to the Meta Information Module. This module now contains **information about people and organisations in the field of MAR**, as well as all **references from documents and websites** used in this project (Annex 1).

Two tertiary products were created:

- This **report**, describing and analysing results produced in this project:
    - A review of the products produced in the project is given in Chapter 2
    - In Chapter 3 the conclusions drawn from the database are presented, along with some generic insights that have resulted from the review of the many information sources.
    - In Chapter 4 some indications are given for possible follow up activities building on the results produced in this project. It also contains some ideas for the role of IGRAC in the dissemination of MAR related information.

- A **fact sheet** for distribution in seminars and to accompany the questionnaire (Section 2.7 and Annex 9).

2 RESULTS AND PRODUCTS

2.1 Classification of MAR techniques

A great benefit of MAR technology is that it is flexible and can be used for many purposes and applied at a range of scales. The great variety of MAR techniques available, and the varying site specifics, has lead to a large variety in scheme design and construction. A classification of MAR technologies in a synoptic table provides an overview of all possible MAR technologies, and allows referencing with other MAR applications using similar technologies. The classification of MAR techniques by Ian Gale (2005) is used as a guideline for the creation of the classification table shown in table 3.

Table 3: MAR classification: Overview of MAR techniques and sub techniques.

	Technology	Sub type	
Techniques referring primarily to getting water infiltrated	Spreading methods	infiltration ponds & basins	
		flooding	
		ditch, furrow, drains	
		irrigation	
	Induced bank infiltration		
	Well, shaft and borehole recharge	deep well injection	AS(TR)
			ASR
		shallow well/ shaft/ pit infiltration	
Techniques referring primarily to intercepting the water	In-channel modifications	recharge dams	
		sub surface dams	
		sand dams	
		channel spreading	
	Runoff harvesting	barriers and bunds	
		trenches	

MAR applications are subdivided in 5 principal techniques and 14 sub-types. The main techniques are chosen in relation to the type of technique used to either intercept the water or to getting the water infiltrated. The sub types are specific engineering techniques that are applied, many of which are known to stakeholders or often cited in references. Induced bank infiltration is a distinctive technique which cannot be listed under any other main MAR technique. Therefore it is assigned to a separate class where it is both technology and sub-type.

AS(TR) is Aquifer Storage (Transfer and Recovery), ASR is Aquifer Storage and Recovery. Short explanations of the MAR techniques and sub techniques listed in the classification are given in Annex 2.

2.2 MAR Questionnaire

Contact persons and users of the IGRAC website are given the opportunity to add regional information about MAR to the information on the IGRAC website by filling in a questionnaire. The questionnaire has been based on the earlier inventory of the IAH-MAR commission in 2002.

The questionnaire is in essence a table where a combination of a MAR technique with a certain attribute to this technique can be selected (Annex 3). The classification of MAR techniques (Section 2.1) has been used to represent the MAR techniques that can be selected. The attributes provide further information about the MAR technique that has been used in a certain region. Similar to the subdivision of MAR techniques, the attributes have also been subdivided into main attributes and sub attributes. Short explanations of the main attributes are given below:

- **Source**: The source of water used by the MAR technique
- **Use:** The group of users profiting from the MAR technique
- **Management**: The purpose of the MAR technique from a water management perspective
- **Scale:** The average scale of schemes of a MAR technique
- **Geology:** The geological composition of the aquifer being recharged
- **Number of schemes**: The number of schemes of each MAR technique
- **(Estimated) total capacity** (m^3/year): The total capacity of all schemes of a MAR technique.

For short explanations of the sub attributes, refer to Annex 4.

At present (March 2007) 6 persons have responded on the questionnaire (Annex 11). Promotion and spreading of this questionnaire is greatly encouraged. The questionnaire has been placed on the website of the International Association of Hydrogeologists (IAH): http://www.iah.org/recharge/inventory.html

2.3 MAR Scheme Database

General information

An inventory of MAR schemes can provide valuable information about the extent of use of MAR technology in the world, and the potential for further development of these technologies in areas with groundwater related issues. The MAR scheme data base contains information about MAR schemes applied around the world. Each project, or case, is described through a fixed set of attributes (Annex 5). These attributes are mostly the same attributes as the ones used in the MAR questionnaire (Section 2.2). The main attributes that have been added to the ones described in section 2.2 are:

- **Location**: The location of the MAR scheme on country and state level.
- **Rainfall**: Annual rainfall on the location of the MAR scheme.
- **Costs**: Construction costs of the MAR scheme
- **Status**: Operational status of the MAR scheme. When schemes are in the pilot stage this can also be indicated here.

Data structure

All numeric data in the database are given in ranges. All data in de database are in the metric system, time is given in years, the currency used is the US$.

For some attributes a primary and secondary input has been given to provide a more accurate description of schemes where multiple attributes of the same group are used simultaneously. Some MAR schemes for instance apply more than one MAR technique for infiltration of water. This water can also be drawn from multiple sources, and the scheme can serve multiple purposes. A maximum of two attributes within the same group has been described in the MAR scheme database.

Because of the large variety in scheme scale and design, scheme entry in the MAR database is not straight forward. In most cases an individual scheme has been described in literature, which has subsequently been entered in the MAR database. This works fine for large scale schemes, but very small scale schemes cannot be so easily discerned. Bunds for example are typically constructed in larger scale water and slope management projects, in which case no data about individual bunds are available. Listing all individual bunds in an integrated system can then be difficult and time consuming. Therefore the attribute ‘number of individual schemes’ has been added, so that the number of individual schemes can be added if known. Quantitative attributes such as ‘scheme capacity’ or ‘scheme costs’ in these cases apply to all the schemes that are part of the entry in the database. Care has been taken not to create “double entries” (schemes that have both been entered in the database as individual entry and as entry in integrated schemes).

Users of the IGRAC website will not have access to the MAR scheme database directly. Instead they can either select schemes through the case-based reasoning search mechanism (Annex 1) or indirectly use information from the MAR scheme database by accessing the Global Overview Module (Annex 1).

Present status of MAR scheme database

At present the MAR scheme database contains 449 scheme entries applied in 60 countries around the world. An overview of the number of schemes in the MAR database per country, region and MAR main technique of the scheme is given in

Annex 6. An overview of the number of schemes recorded in the MAR database for each type of information source is given in Table 4.

Table 4: Overview number of schemes in database per information source type

Information source type	Number of schemes in database
Literature	280
Internet	135
Personal communication	12
Literature & internet	9
Literature & personal communication	11
Internet & personal communication	2

2.4 Inventory of Information Sources

During this project an inventory of information sources has been made, compiling all references of information gathered from literature, websites and contact persons for this project. A table has been added to the references, containing an indication of the MAR main technique and the region that has been described in the literature or website referred to by the reference. The inventory of information sources has been used to add references about MAR to the Meta Information Module (Annex 1) on the IGRAC website, and is therefore not shown or described in detail in this report.

2.5 MAR Technical Descriptions

More detailed information on the 5 main MAR techniques as defined in the MAR classification (Section 2.1) is given in the MAR Technical Descriptions (Annex 7).

Each MAR main technique is described according to its general features and the sub techniques belonging to the MAR main technique. The design features of the MAR technique are described in general, and advantages and constraints for implementation of the technique are given. Each of the 5 most important main attributes that are used in the questionnaire and scheme database are described in an 'Attributes overview' section. Illustrative pictures and schematic drawings have been added to give readers an instant grasp of the MAR technique that has been described.

2.6 MAR Case Studies

In order to provide detailed case-specific information, exemplary schemes from the MAR scheme database have been selected, and these schemes have been described in detail in 5 case studies (Annex 8). These case studies illustrate the 5 main MAR techniques under a variety of natural conditions, and provide insight in the practical application of MARS technologies. Each case study is set in a different part of the world, and for each main MAR technique a case study of different scale, from small to large, was selected. This was done in an attempt to display the wide range of MAR techniques available for different applications.

The format in which the case studies are written was largely adopted from the Netherlands Water Partnership (NWP, 2006), where this format was originally used for description of case studies in the upcoming publication 'Smart Water Harvesting Solutions'. The case studies are described in 4 main sections:

- **General information**, where a description of the location and situation of the case study is given. Illustrative pictures and figures of the case study are added.
- **Technical information,** where (technical) information about the MAR technique applied in the case study is given.
- **Financial information,** where information about management of the scheme, and the scheme costs and benefits is given.
- **General conclusions,** where the application of the MAR technique in general and on the location of the case study is evaluated, and the potential for application of the technique at other locations is assessed.

2.7 Fact Sheet

The fact sheet gives a short description of this project for distribution in seminars and to accompany the questionnaire (Annex 9). The first part contains information on MAR and explains why MAR is becoming important. The second part is about the project, explaining why the project was carried out and listing the results produced during the project. The information in the fact sheet is complemented with the classification table and a picture of the infiltration ponds in the MAR scheme of Atlantis, South Africa.

3 DATA ANALYSIS

3.1 Data analysis of MAR Scheme Database

Annex 10 contains an analysis of the data stored in the database. It provides an overview of the number of cases that are available in the database per main MAR technique for each attribute in the database (see Annex 5). Graphs are explained shortly below:

Rainfall at scheme locations

- Most cases in the database are in the 250 – 600 mm/year class (semi-arid regions). In semi-arid regions, source water is often scarcely available under natural circumstances. MAR techniques can infiltrate this source water before flowing out of the catchment, thereby increasing the amount of water in storage.
- *Spreading methods* and *runoff harvesting*, and to a lesser degree *in-channel modifications*, are the MAR techniques in the database which are applied the most at the lowest rainfall regimes. These techniques are in general relatively cheap and easy to construct, and therefore more suitable for application in the, often poor, arid and semi-arid regions of the world. Also, *runoff harvesting* techniques and *in-channel modifications* simultaneously intercept and infiltrate the source water. This means that these schemes can infiltrate the source water when it arrives at the location of the scheme (after rainfall), instead of relying on other techniques to deliver water for interception.

Aquifer type at scheme locations

- Most schemes infiltrate water in aquifers consisting of unconsolidated sediments. This is possibly because unconsolidated sediments, more often than other aquifer types, possess favourable geohydrological properties for infiltration and storage of water, such as high vertical permeability and high porosity.
- *Spreading methods* and *induced bank infiltration* are often applied for drinking water supply. Sandy unconsolidated aquifers are favourable for these technologies, because these aquifers allow rapid infiltration of source water and have water purifying qualities. This is reflected by the high number of *spreading methods* and *induced bank infiltration* schemes in the database that infiltrate water in aquifers consisting of unconsolidated sediments.
- *Well, shaft and borehole recharge* is often used to store water in deep aquifers. Limestone aquifers can have large storage capacities when solution enhanced fractures are present (Gale et al. 2002) and are therefore relatively often selected for *well, shaft and borehole recharge*. This is reflected in the results from the database.

Scheme source of water

- *Spreading methods* on sandy soils are sometimes used to infiltrate treated waste water. The purifying effect of sand is used to further treat the wastewater as it infiltrates.
- *Induced bank infiltration* schemes are almost always placed near permanent water bodies with highly permeable banks to ensure a continuous water supply to the abstraction wells. This is why most *induced bank infiltration* schemes use source water from perennial streams.
- *In-channel modifications* are often placed in streambeds of intermittent water courses to infiltrate discharge resulting from erratic rainfall events. This is reflected in the database results.
- *Runoff harvesting* techniques are, as the name implies, used to catch and infiltrate runoff (overland flow) from fields and hill slopes. This explains the high value in the graph for overland flow.

Scheme use purpose

- Schemes having the use purpose of either domestic water supply or agricultural water supply are much more widespread than schemes having the purpose of industrial water supply or ecology & environment. This is reflected in the graph.
- *Induced bank infiltration* schemes are often large scale, expensive and complicated systems, and are therefore most often applied to deliver drinking water to cities and areas with high population densities. This explains why most schemes in the database are applied for domestic water supply.
- *Runoff harvesting* systems usually enhance infiltration of water that has been flowing over the land surface. The infiltrated water is highly variable in quality (Gale I. et al. 2002), and usually not suitable for drinking, but serves mostly to increase volumetric soil moisture in order to increase agricultural benefits. This explains why most *runoff harvesting* systems are applied for agricultural purposes.

Scheme management purpose

- *Induced bank infiltration* schemes and *runoff harvesting* schemes are usually not well described in literature with respect to their purpose from a management perspective, explaining the low values of these MAR techniques in the graph.
- The most common management purpose that is being applied, is storing groundwater for later use (Ministry of Water and Forestry of South Africa, 2005). This is reflected in the graph for the parameter ‘groundwater storage control’. *Spreading methods* and *well shaft and borehole recharge* are also frequently used for quality improvement of groundwater, or to prevent or retard seawater intrusion.
- Floodwater resulting from large rainfall events is usually controlled by constructing *in-channel modifications*, explaining the relatively high value for floodwater control at this MAR technology.

Scheme scale

- *Induced bank infiltration* systems often have the purpose of supplying large amounts of drinking water to densely populated areas, and are therefore usually large scale systems.
- *Runoff harvesting* schemes are usually constructed by local people in dry regions with high surface runoff after erratic rainfall events. These schemes usually infiltrate relatively small amounts of water and are therefore usually small scale systems.
- *Spreading methods* are very diverse and can have highly variable scales. The reason for the strong prevalence of large scale systems indicated in the graph is probably because large scale schemes are better described in literature and therefore more information on large scale schemes is available in the MAR scheme database.

Scheme construction costs

- Little is known about costs of *induced bank infiltration* schemes and *runoff harvesting* schemes in the scheme database. *Induced bank infiltration* systems are often complex systems of abstraction well galleries built in different periods and often linked with other MAR technologies, making an estimation of total costs difficult. However, it is safe to say that costs of these schemes usually exceed 1 million US$ easily.
- *Runoff harvesting* schemes are often constructed by individuals or local communities using locally available materials. The costs of these schemes is often in man hours spend by the builder, and difficult to express in dollars. But generally costs rarely exceed 50 000 US$.

Scheme funding source, scheme owner, scheme management

- *Spreading methods* and *well, shaft and borehole recharge* schemes in the database are mostly funded and managed by public companies, municipal water authorities and governments. This result is probably influenced by selective input of schemes in the database. This happens because medium and large scale systems are generally better described in literature and on websites, and these schemes are mostly funded and managed by municipal authorities and governments. Much less data are for example available about small scale *spreading methods* in India than about large scale *spreading methods* in the USA, although small scale water spreading schemes in India are probably much more widespread than large scale schemes in the USA.
- Few data are available on the funding source of *induced bank infiltration* schemes, but because of the high costs of these systems, these will mostly be funded by municipal water authorities and the government.
- *In-channel modifications* are usually funded and managed by governments. This is probably because these schemes often have management purposes such as floodwater control or groundwater storage control, which are typically managed by government departments. In the case of recharge dams, schemes can also be very large and expensive.
- *Well, shaft and borehole recharge* is sometimes applied by private industries (mostly ASR or ASTR wells). This is usually done to provide groundwater storage control or water quality improvement for industries requiring either large amounts of water, or water of high quality.

- *Runoff harvesting* schemes are usually small scale systems, applied and managed mostly by individuals and local communities. This is reflected in all three graphs.

Besides giving overviews of the number of cases that are available in the database per main MAR technique for each attribute in the database, it's also possible to provide a more detailed insight into each attribute. In this way there is a large variety of detailed graphs possible, a few possibilities are shown in Annex 10, and described shortly below:

Scheme management of infiltration ponds and recharge dams

An advantage of looking into more detail to an attribute for each MAR sub-technique is that various sub-techniques can be compared to each other with respect to a certain attribute. In annex 10 an example is provided, showing in percentages the various scheme management actors for the MAR sub-techniques *Infiltration ponds* and *Recharge dams.*

- Generally, *infiltration ponds* are installed for use purposes such as supply of drinking water or irrigation water, and therefore are usually managed by instances responsible for water supply on a local to regional level, like municipal water authorities. *Recharge dams* often have management purposes such as floodwater control or groundwater storage control, which are purposes that are mostly managed by instances operating on a higher level, like governmental agencies.

Scheme management for MAR sub-techniques

An overview of scheme management can also be provided for all MAR sub-techniques. This is essentially the same graph as the one giving an overview of scheme management for the MAR main techniques, described above, but providing more detail.

- It is likely that schemes managed by NGO's or private companies are not well represented in the database. There are without doubt more MAR schemes that are managed by private companies, but privately managed schemes are usually not well described in literature.
- The relatively high amount of cases in the database for *recharge dams* managed by government/international agencies is reflected in the graph, as well as the relatively high amount of cases in the database for *infiltration ponds* managed by public companies/(municipal) water authorities.
- Another point of interest is the relatively large number of *barriers and bunds* being managed on a community level. *Barriers and bunds* are structures that are relatively easy and cheap to construct and maintain. The effect on the recharge of groundwater is usually limited, but these structures can also protect soils against erosion. This is why generally *barriers and bunds* are constructed and maintained by local communities and farmers who apply these structures on their lands.
- The relatively large number of *ASR wells* being managed by public companies/(municipal) water authorities also sticks out. Like infiltration ponds, *ASR wells* have generally been installed for use purposes such as supply of drinking water or irrigation water, so these structures are generally managed by instances responsible for water supply on a local to regional level, such as public companies or (municipal) water authorities.

3.2 Reflection on the data analysis

An intensive collection of information from literature, web search and contact persons during this project, has resulted in a large MAR knowledge base. This resulted in some general conclusions and observations about the application of MAR techniques that are complementary to the analysis in the previous section. These are described in the following section.

Scale and cost of MAR applications

MAR applications show a wide variety in scale and cost depending the type and purpose of the scheme.

- Most MAR techniques for rural water supply are **small scale**. This includes most of the run-off harvesting systems and shallow well /pit infiltration, and part of the spreading methods and in-channel modifications (sand dams and sub surface dams). These systems are usually designed, constructed and managed with a high degree of community participation. There are many different types and technologies of small scale MAR techniques in many countries, some them dating back to ancient times. Many of them are described in literature or on the internet, but generally there is a lack of documented data on design, cost, effectiveness and operational experiences. Typical cost of these systems are in the order of US $ 0,1-0,3/m^3.
- **Medium type** systems are usually characterized by a higher degree of technical complexity and a need for more professional expertise in design, construction and management. Usually, construction is done by contractors and the management responsibility has been assigned to (municipal) authorities or agencies. Typical examples are recharge dams and ASR/AS(TR) systems. These systems are generally well described, like the recharge dams in the Middle East and the ASR/AS(TR) systems in the US and Australia. There is little information on the investment cost and cost per m^3, but it may be expected that despite higher investment cost, the cost per m^3 should be lower if the systems are efficiently used and operated (economy of scale)
- **Large scale** systems are usually implemented by national authorities or urban water supply companies for water supply to large cities or for irrigation water supply. These include the bank infiltration systems and spreading basins for large cities, large (often multi-purpose) recharge dams and large conjunctive use systems for infiltration of irrigation water.

Spatial distribution of MAR schemes

It is no surprise that MAR techniques were first applied in the world's arid regions like the Middle East, where long dry periods forced the population to store water for drinking water purposes. Ancient water conservation structures are known throughout the Middle East and MAR techniques are still high on the water management agenda in many Middle East countries. Typical medium sized technologies in this region are recharge dams (in wadi's) and deep well injection.

Also in the Mediterranean countries of Europe (South Spain, Greece, Mediterranean Islands) there is a growing interest in medium sized MAR applications to cope with increasing water demands and longer dry periods.

Smaller in-channel modifications, run-off harvesting systems and shallow well infiltration schemes are found in many countries in Africa, Asia and Latin America, often constructed in rural areas with the help of local NGO's. The number of schemes is difficult to guess, as there are no systematic records of these community based schemes.

The exception is India, where the construction of these systems is also part of the national/state water policy. This has made India the frontrunner of the application of MAR techniques in Asia, with thousands of small scale MAR schemes of different types and often with specific local names.

Riverbank infiltration and infiltration ponds are common technologies in Europe for large scale urban water supply, water quality improvement and strategic storage. ASR techniques are increasingly applied in Europe and other high income countries like Australia and the US, which is the leading country in development of ASR technology.

Annex 6 gives the distribution of the MAR technologies per country from the systems in the MAR data base.

Infiltration capacity of MAR schemes

Table 5 gives a summary of the average annual infiltration capacity of the different scheme types.

Table 5: Estimated average infiltration capacity of MAR sub techniques

Technology	Sub type		Annual infiltration per unit (Million m^3/year)
Spreading methods	infiltration ponds & basins		0,1-0,5 mm/day (higher in course clean sands), infiltration depending on unit surface area
	flooding		
	ditch, furrow, drains		no data available
	irrigation		3 mm/day, infiltration depending on surface area
Induced bank infiltration			5-25 Mcm (million m3) with extremes to 150-200 Mcm, schemes consisting of numerous abstraction wells
Well, shaft and borehole recharge	deep well injection	AS(TR)	0,1-1,0 Mcm
		ASR	
	shallow well/ shaft/ pit infiltration		< 0,1 Mcm
In-channel modifications	recharge dams		0.1-1 Mcm (depending on length of structure)
	sub surface dams		0,005-1 Mcm (depending on length of structure)
	sand dams		0,005-0,01 Mcm
	channel spreading		5-50 Mcm per scheme, often consisting of numerous individual structures
Runoff harvesting	barriers and bunds		<0,1 Mcm, Infiltration depending on length of structure
	trenches		

Obviously the small scale MAR schemes have lower infiltration rates, but their total infiltration may be substantial due to the large number of structures. For example, sand dams have an infiltration capacity of 0,005-0,01 million m^3/year per unit, but these can be constructed in cascades of 20-30 dams in one stream at 500 m distance and therefore provide 0,1-0,2 million m^3 recharge per year over a length of 10 km.

The table illustrates that is difficult to make an estimate of average infiltration capacity for most MAR techniques, but the information has been used (in combination with the number of schemes per country in Annex 6) for the following classification of the total annual artificial recharge per country:

Lowest:	<50	million m^3/year
Low:	50-200	million m^3/year
Medium:	200-2,000	million m^3/year
High:	>2,000	million m^3/year

Main advantages and constraints of different MAR techniques

Some of the information sources give information on specific advantages and good practices or about constraints encountered during design. In the table below we have tried to summarize these issues for the different sub systems (Table 6).

Table 6: Main advantages and constraints of MAR sub techniques.

Technology		Main advantages and constraints	
		advantages	constraints
infiltration ponds & basins		infiltration of large quantities of water at relatively low cost, maintenance and anti-clogging procedures relatively simple, organic contaminants in source water filtered out in soil	requires large flat permeable surface area, potential for surface water related breading of disease vectors, potential for water pollution, potential for high evaporation
flooding		infiltration of large quantities of water at relatively low cost	
ditch, furrow, drains		in case of reversed drainage, structures can be installed underground, and therefore do not interfere with land use	requires large permeable surface area, potential for surface water related breading of disease vectors
irrigation		costs limited due to use existing facilities	
Induced bank infiltration		large quantities of good quality water can be withdrawn, organic contaminants in source water filtered out in soil	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging
deep well injection	AS(TR)	infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging, high quality requirements of source water
	ASR	clogging partially removed during recovery cycle, infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high quality requirements of source water
shallow well/ shaft/ pit infiltration		use of existing facilities reduces costs, recovery from same structure reduces clogging	high quality requirements of source water
recharge dams		structures are installed in streambeds, and therefore do not interfere with land use	breached structures may result in significant damage downstream
sub surface dams		low cost structures, community based, low maintenance, structures are installed in streambeds, and therefore do not interfere with land use	potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water, quality control of the structure difficult
sand dams			potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water
channel spreading		low cost technique, structures are installed in streambeds, and therefore do not interfere with land use	structures are easily breached during high runoff
barriers and bunds		low cost technique, simple design, simple construction, simple operation and maintenance, prevents soil erosion as well as recharging the groundwater.	infiltration of relatively small quantities of water
trenches			

4 WAY FORWARD: GLOBAL MAR INFORMATION

4.1 Growing importance of MAR application

Provision of sufficient storage capacity under growing water demand and increasing climate variability is one of the main concerns for water managers in the coming decades. Accurate estimates for the required storage capacity do not exist, but it is expected that in the near future additional storage capacity will be needed to maintain even minimum supply levels to millions of people, both in rural and urban areas. In light of the limitations of large dams (see also Chapter 1), MAR can be considered a serious alternative to surface water storage for maintaining water supply levels in the future (Tuinhof et al. 2004).

4.2 Role of IGRAC in Global MAR Information

This global MAR inventory has provided a set of valuable outputs (see Chapter 3) that are available to users and stakeholders through the IGRAC web site. The results form a good basis for dissemination and for stimulating the broader application of MAR around the world. Follow up activities could further enhance this and contribute to recognition of IGRAC as a valuable resource for the dissemination and sharing of MAR related information, in collaboration with and complementary to the IAH-MAR Commission and UNESCO-IHP.

4.3 Activities for 2007

Activities that could be carried out in 2007 as a follow up to the present inventory can be sub divided in three categories:

- Activities to promote the dissemination of the present results.
- Activities to enhance the scheme data base and Global Overview module.
- Activities to increase the application of MAR.

Activities for dissemination

- Preparation of a fact sheet for distribution through IGRAC, IAH and UNESCO. A draft fact sheet is attached (Annex 9).
- Preparation of a presentation, giving a summary of this inventory in the broader framework of the importance of groundwater storage (in relation to surface water storage behind dams), the role of groundwater storage as climate change adaptation strategy and others. This will be used at the plenary session preceding the ISMAR 6 conference in October 2007.
- Preparation of a poster presentation for the ISMAR 6 conference.

Activities to enhance the information data base

- Add entries in the case data base by (i) sending fact sheet together with a reminder to the recipients of the questionnaire and (ii) continue the web search for selected countries and (iii) collect case information from the participants of the ISAR 7 conference
- Add more carefully selected case studies from literature and internet sources. Adding more case studies will improve representation of the broad variety of different MAR sub techniques within each MAR main technology. Also these case studies can help to gain further insight in the practical application of MAR around the world.
- Collect more information on the cost and economics of MAR techniques to show the cost effectiveness of MAR compared to other solutions (table 2)

Activities for promotion of MAR application

- Preparing guidelines for small scale (rural) MAR technology selection (from the perspective of an imaginary user).
- Preparing a tool using GIS and remote sensing technology to determine potential locations for the application of MAR sand dams.

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http://cpreec.org/04_phamplets/19_traditional_water/traditional_water.html

http://www.igrac.nl

Annexes

ANNEX1: Presentation on IGRAC website

On the IGRAC website, information on the globe's groundwater is made available to the public through three main entries:

- Global Groundwater Information System (GGIS): envisaged as a platform for exchanging and disseminating area-specific information on groundwater on a global scale.
- Guidelines and Protocols: intended to stimulate and improve observation of groundwater parameters and variables, mainly through methodological assistance.
- Special projects: providing information on a variety of projects IGRAC is involved in.

All products from this MAR project are gathered under the section 'Artificial Recharge' in the entries of *Special projects* and *GGIS* on the IGRAC website.

Special projects entry

Products that are accessible in the S*pecial projects* entry under the section 'artificial recharge' contain information that will provide insight in MAR techniques and applications to the user. The following subsections have been created:

- An introduction about MAR,
- The classification of MAR techniques
- Description of the 5 main MAR techniques, coupled with the 5 case-studies

Global Groundwater Information System (GGIS)

The *Global Groundwater Information System (GGIS)* was designed as a modular system. Data produced in this project will be presented via two modules:

1. Global Overview Module

Information from the MAR scheme data base is used along with the response on the questionnaire sent to the contact persons, to provide a world wide overview of MAR applications. This overview is presented to the user in the Global Overview Module on the IGRAC portal (Figure 1). The Global Overview Module has been updated to contain a new section called 'Artificial recharge', where a user can choose between 7 attributes; the 5 main MAR technologies, estimated total number of schemes and estimated total infiltration capacity. The selected attribute will then be presented graphically per country on a global scale in the module. When results are displayed for a selected attribute, a link is provided per country, to information available in the Meta Information Module.

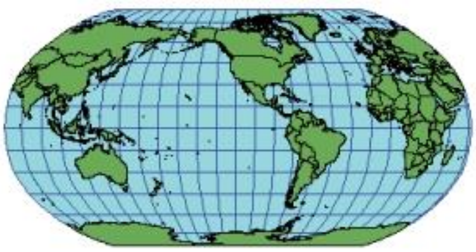


Figure 1: The Global Overview Module on the IGRAC portal (www.igrac.nl)

2. Meta Information Module (MIM)

This module has been updated to contain the references that were used per country for each of the attributes that can be selected in the Global Overview Module (Figure 2). The MIM also contains relevant information about people, organizations, documents and websites.

Figure 2: The Meta Information Module on the IGRAC portal (www.igrac.nl)

Case based reasoning search mechanism

Information from the MAR scheme data base is not only accessible through the Global Overview Module, but also through a sophisticated 'case based reasoning' search mechanism. This search mechanism has been created especially for this project to provide information on specific schemes of interest to the user. The user is able to make a selection on schemes ('cases') in the MAR scheme database by providing a series of search criteria to the search mechanism. The search mechanism returns schemes matching the search criteria selected by the user from the MAR scheme database. These search criteria include the following main attributes:

- Country
- State
- Annual rainfall
- Aquifer type
- Type of infiltration technique (MAR technique)
- Source of water
- Use purpose
- Management purpose
- Scale
- Costs
- Operational status

ANNEX 2: Short descriptions of MAR techniques from classification

Spreading methods: Water spreading is applied in cases where the aquifer to be recharged is at or near to the ground surface, and the surface consists of permeable material. Most water spreading schemes use a system of ditches and banks, or pipes to convey water to the spreading area, and to control the spreading process.

- Infiltration ponds and basins: These structures are either excavated, or are enclosed by dikes or levees which retain the recharge water until it has infiltrated through the floor of the basin.
- Flooding: Water is spread as a thin sheet, which moves at a minimum velocity to avoid disturbance of the soil cover.
- Ditch, furrow, drains: A system of shallow, flat bottomed and closely spaced ditches and furrows is installed through which water is introduced and allowed to infiltrate. Underground networks of perforated drainage conduits, from which later infiltrates into the soil, are also included here.
- Irrigation: In irrigated areas, water can be deliberately spread by irrigating cropland with excess water during dormant or non-irrigating seasons. Sprinkling techniques are also included here.

Induced bank infiltration: These systems commonly consist of a gallery or a line of boreholes. These are placed at a short distance from, and parallel to the bank of a surface water body. Pumping of the boreholes lowers the water table adjacent to the river or lake, inducing this water to enter the aquifer system.

Well, shaft and borehole recharge: Structures designed or adapted to recharge the groundwater by injection or infiltration of water.

Deep well injection: A technique used where thick, low permeability strata, overlie target aquifers, in order to recharge water directly into the aquifer.

- AS(TR): Aquifer Storage (AS) involves water injection through a borehole into a deep aquifer, without recovery of the water. Aquifer Storage, Transfer and Recovery (ASTR) is the same technique, but with recovery from another borehole, some distance away.
- ASR: Aquifer Storage and Recovery (ASR): Aquifer Storage & Recovery is a technique where the borehole is used for both injection and recovery of water.
- Shallow well/ shaft/ pit infiltration: These structures are used to recharge shallow aquifers, especially at locations where surface layers are of low permeability and spreading methods are not effective.

In-channel modifications: Structures that intercept or detain the stream flow through a natural drainage channel, and enhance the natural groundwater recharge. Generally, the purpose is to enhance groundwater recharge by storage of flood events and a controlled release, in order to facilitate its infiltration into the subsurface.

- Recharge dams: Groundwater recharge dam are designed to collect stream runoff water in a surface water reservoir upstream of the dam. To provide recharge to groundwater, either the surface water reservoir upstream of the dam serves as a percolation pond, or water is released through pipes or an open channel to infiltrate into the downstream riverbed.
- Sub surface dams: Poorly permeable underground barriers designed to slow down or stop underground flow in an aquifer. They create a zone of enhanced groundwater storage upstream of the dam, raising the water table.
- Sand dams: Structures constructed above ground in intermittent streams. During periods of high flow, sand and gravel accumulates against the dam. Runoff water can easily infiltrate these highly permeable soil deposits, creating an artificial aquifer upstream of the dam.
- Channel spreading: These techniques increase the wetted area and infiltration rate of the streambed. Widening, levelling, scarifying, dredging, and the use of “L”-shaped levees are all examples of this technology.

Runoff harvesting: This includes all techniques to collect overland flow for productive use. It usually involves the concentration of rainfall or overland flow from a larger area for use in a smaller area as soil moisture, or for recharging the groundwater.

- Barriers and bunds: These structures act as an obstruction to overland flow on hill slopes. Flow velocity is reduced, and water percolates behind the structure, increasing soil moisture and/or recharging the groundwater
- Trenches: These man-made depressions in the hill slope or in paved surfaces will catch overland flow and infiltrate it through the bottom and sides of the structure, thus increasing soil moisture and/or recharging the groundwater.

ANNEX 3: MAR Questionnaire

IGRAC Global Inventory of Artificial Recharge

Country/ State		Name		E-mail	
		Position		Date	

	Technology:	A. Techniques referring primarily to getting water infiltrated								B. Techniques referring primarily to intercepting the water					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub type:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well injection		shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:						AS(TR)	ASR							
source	rainwater [1]														
source	overland flow														
source	intermittent water courses [2]														
source	perennial streams [2]														
source	lakes & artificial reservoirs [3]														
source	treated waste water														
source	aquifer (groundwater) [4]														
use	domestic water supply														
use	industrial water supply														
use	agricultural water supply														
use	ecology & environment														
managem	quality improvement														
managem	seawater intrusion control														
managem	groundwater storage control														
managem	groundwater level control														
scale	small (scheme capacity < 100 000 m³/year)														
scale	medium (capacity 100 000 - 1 000 000 m³/year)														
scale	large (scheme capacity > 1 000 000 m³/year)														
geology	unconsolidated sediments														
geology	sandstone														
geology	limestone														
geology	other rock formations														
Nr. of schemes															
(estimated) total capacity (m³/year)															

1 Includes rooftop RWH
2 Includes diversion dams
3 Includes storage dams
4 Includes well/ borehole interception

ANNEX 4: Short descriptions of sub attributes in questionnaire

Source

Rainwater: Downward moving atmospheric water before it hits land surface.

Overland flow: Storm flow water originating from rainfall and running off over the land surface before it reaches a channel.

Intermittent water courses: Streams experiencing periods without flow during a normal year.

Perennial streams: Stream experiencing flow throughout the year, e.g. large rivers and canals.

Lakes & artificial reservoirs: Large bodies of water contained by land, some are man-made.

Treated waste water: Recycled used water, which has undergone some form of treatment to improve quality.

Aquifer (groundwater): Water taken from a source aquifer for use in another (target) aquifer.

Use

Domestic water supply: Water used for domestic purposes, e.g. for drinking, cooking, washing, cleaning, etc.

Industrial water supply: Water used for industrial purposes.

Agricultural water supply: Water used for agricultural purposes, e.g. irrigation.

Ecology & environment: Water is used or controlled with the purpose of maintaining or improving local ecology and environment.

Management

Quality improvement: Recharge of water to improve the quality of water in an aquifer.

Seawater intrusion control: Recharge of water to control or prevent intrusion of sea water in an aquifer.

Groundwater storage control: Regular and strategic groundwater storage to bridge gaps between demand and supply and combat over-exploitation.

Groundwater level control: Maintaining groundwater levels at the optimum position from the point of view of special functions, e.g. agriculture, ecosystems or the environment (including preventing land subsidence).

Scale

Small: Scheme capacity of system between 0 and 100 000 m^3/year.

Medium: Scheme capacity of system between 100 000 and 1 000 000 m^3/year.

Large: Scheme capacity of system larger than 1 000 000 m^3/year.

Geology

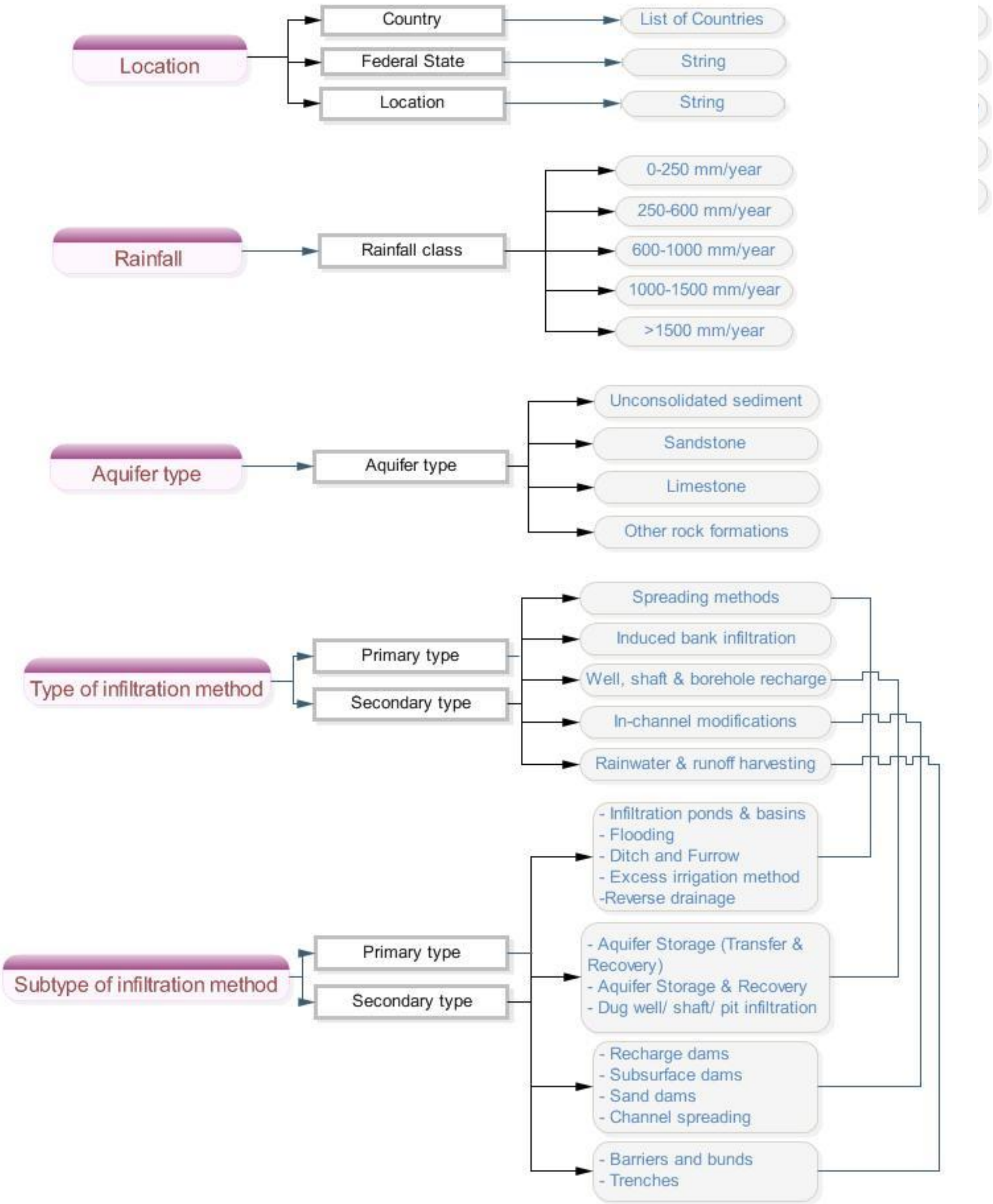
Unconsolidated sediments: Any type of unconsolidated sedimentary formation.

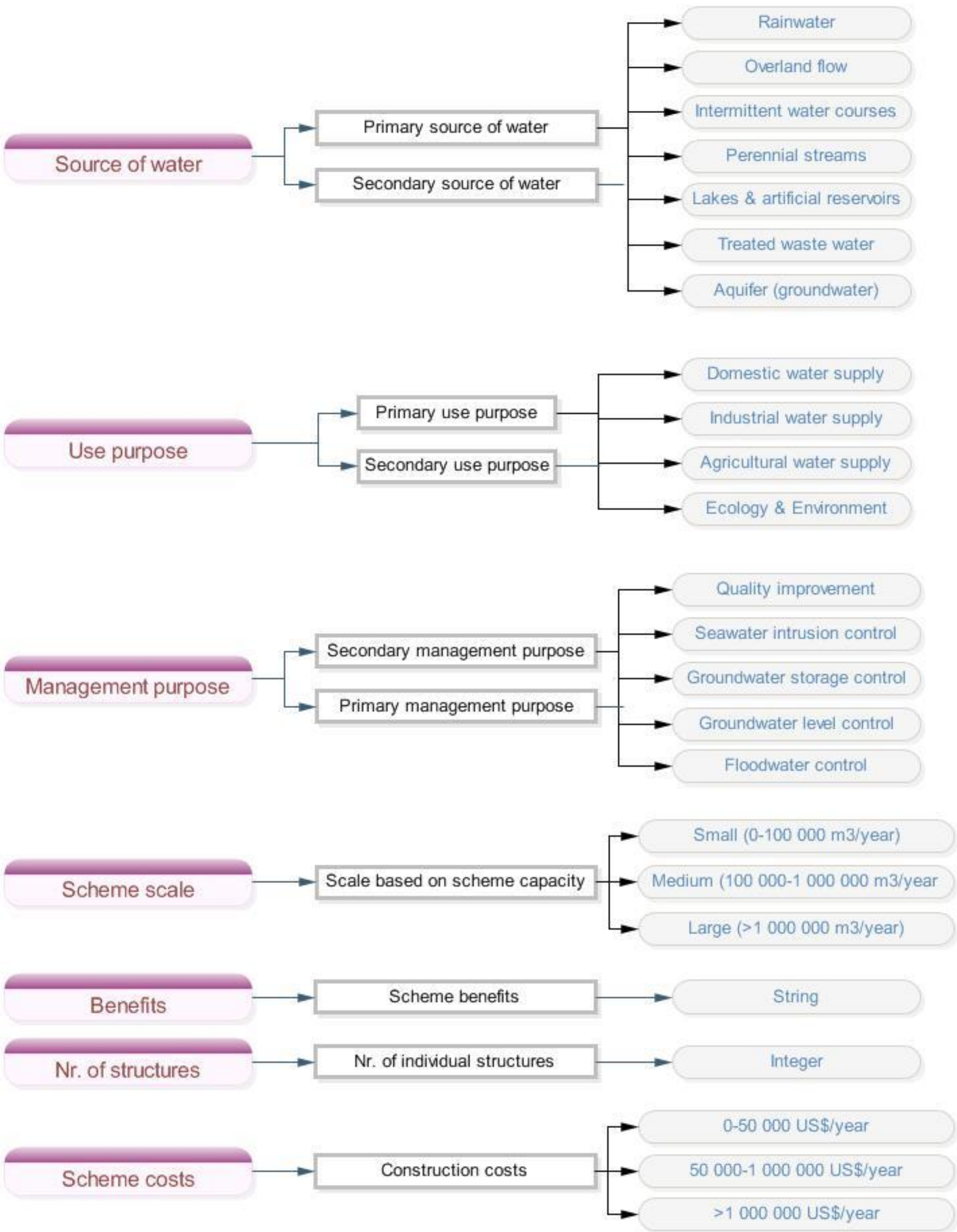
Sandstone: Consolidated sedimentary rock composed largely of small grains of the minerals quartz and feldspar.

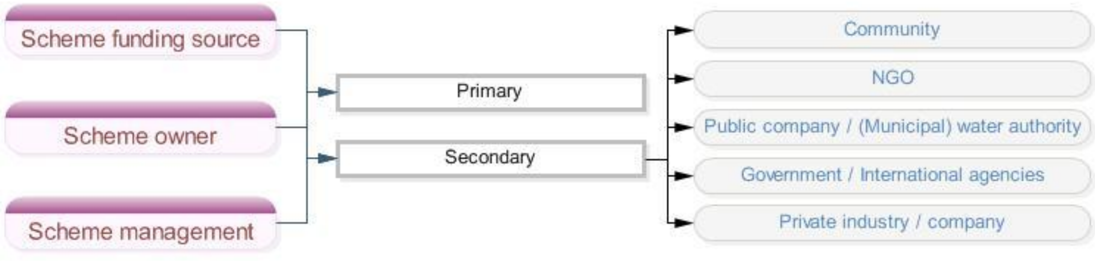
Limestone: Consolidated sedimentary rock composed largely of calcium carbonate ($CaCO_3$)

Other rock formations: Any type of rock not mentioned above

ANNEX 5: Attributes in MAR Scheme database




Source of water
Primary source of water
Secondary source of water
Rainwater
Overland flow
Intermittent water courses
Perennial streams
Lakes & artificial reservoirs
Treated waste water
Aquifer (groundwater)
Use purpose
Primary use purpose
Secondary use purpose
Domestic water supply
Industrial water supply
Agricultural water supply
Ecology & Environment
Management purpose
Secondary management purpose
Primary management purpose
Quality improvement
Seawater intrusion control
Groundwater storage control
Groundwater level control
Floodwater control
Scheme scale
Scale based on scheme capacity
Small (0-100 000 m3/year)
Medium (100 000-1 000 000 m3/year
Large (>1 000 000 m3/year)
Benefits
Scheme benefits
String
Nr. of structures
Nr. of individual structures
Integer
Scheme costs
Construction costs
0-50 000 US$/year
50 000-1 000 000 US$/year
>1 000 000 US$/year


Scheme funding source
Scheme owner
Scheme management
Primary
Secondary
Community
NGO
Public company / (Municipal) water authority
Government / International agencies
Private industry / company


Operational status
Start (year)
Status
year
Fully operational
Partially operational
Pilot project

ANNEX 6: Number of schemes in database per MAR technique and country

Region	Country	Nr. cases	MAR technique: Spreading techniques	MAR technique: Induced bank infiltration	MAR technique: Well, shaft & borehole recharge	MAR technique: In-channel modifications	MAR technique: Runoff harvesting	Estimated annual infiltration (Mcm): < 50	50 - 200	200 - 2000	> 2000
Asia & Oceania	Australia	30	10		19	4				■	
	Japan	1			1			■			
	China	12	3		7	1					■
	Taiwan	1	1					■			
	India	135	21	1	30	91	9				■
	Nepal	5	3		2			■			
	Thailand	1	1					■			
Africa	Namibia	4	1		2			■			
	South Africa	5	2	1	2		1	■			
	Kenya	2				1	1	■			
	Malawi	1					1	■			
	Tanzania	1					1	■			
	Cameroon	1					1	■			
	Cape Verde	2				1	1	■			
	Burkina Faso	5					5	■			
	Chad	1					1	■			
	Niger	2					2	■			
	Mali	1					1	■			
	Morocco	1					1	■			
	Tunisia	2				1	1	■			
	Sudan	2					2	■			
	Somalia	2	1				2	■			
	Sierra Leone	1					1	■			
	Ethiopia	5				1	4	■			
Middle East	Egypt	3	3		1			■			
	United Arab Emirates	9				9			■		
	Oman	7				7			■		
	Iran (Islamic republic of)	9	7			1					
	Syrian Arab Republic	3	1			2					
	Jordan	5	2			3		■			
	Saudi Arabia	1				1					
	Kuwait	2	2					■			
	Israel	1	1						■		
	Occupied Palestinian Territory	3	3					■			
Europe	Russian Federation	1		1							
	Serbia and Montenegro	1		1							
	Slovenia	1		1							
	Romania	1		1							
	Hungary	6	2	5						■	
	Latvia	1		1							
	Slovakia	4		4							
	Czech Republic	1		1							
	Poland	1	1						■		
	Finland	2		2							
	Spain	12	6		8	1		■			
	Austria	2		2							
	Switzerland	3	1	2					■		
	France	2		2							
	Germany	8		8						■	
	Portugal							■			
	Croatia							■			
	UK and Northern Ireland	2		2					■		
	Netherlands	36	6	26	5	1				■	
North & South America	Argentina	2	1			1					
	Brazil	3	1		1	2		■			
	Peru	1	1								
	Paraguay	1	1								
	Mexico	3	3							■	
	Barbados	2	1		1						
	Jamaica	1			1						
	United States of America	83	24		58						■
	Canada	1			1						
	Total	449									

ANNEX 7: MAR Technical Descriptions

Spreading methods

Spreading techniques are among the simplest, oldest, and most widely applied methods of artificial recharge. Water spreading is applied in cases where the aquifer to be recharged is at or near to the ground surface. Recharge is achieved by infiltration through permeable material at the surface, which is managed to maintain infiltration rates. Most water spreading schemes use a system of ditches and banks, or pipes to convey water to the spreading area, and to control the spreading process.

Main application technologies

- Flooding: water is spread as a thin sheet, which moves at a minimum velocity to avoid disturbance of the soil cover. It is only suitable for flat topography.
- Ditch and Furrow system: a system of shallow, flat bottomed and closely spaced ditches and furrows is installed through which water is introduced and allowed to infiltrate. This technique is suitable for both flat and irregular topography.
- Excess irrigation method: in irrigated areas, water can be deliberately spread by irrigating cropland with excess water during dormant or non-irrigating seasons.
- Reverse drainage method: water is piped into underground networks of perforated drainage conduits, from which water infiltrates the soil. This technique is desirable where land is expensive, because it has a negligible effect on surface land use.
- Infiltration basins: basins are either excavated, or are enclosed by dikes or levees which retain the recharge water until it has infiltrated through the floor of the basin.

General features

The rate of infiltration is depends on the nature of the top soil. In situations where there is a reliable source of good-quality input water, and spreading infiltration can be operated throughout the year, hydraulic loadings of typically 30 m/yr can be achieved for fine texture soils like sandy loams, up to 500 m/yr for coarse clean sands. Evaporation rates (0.4-2.4 m/yr) form a minor component of the water balance. Where the source of water contains high loads of suspended solids, management of the recharge structure becomes increasingly important in order to minimize clogging to maintain infiltration rates and keep evaporation from open water to a minimum. Basic monitoring of the sedimentation rate and infiltration rate relative to the estimated rate of open-water evaporation will assist in operational management decisions.

In general, smaller scale spreading techniques are suitable for water supply to medium sized communities and agriculture in rural areas. The often complex and expensive large scale systems are mainly used in industrialized countries. Due to the diversity in spreading techniques and the scale of these techniques, management of spreading schemes occurs on practically all levels. Small scale flooding techniques can be implemented by individual farmers, whereas large scale infiltration basins are often funded and managed by water authorities.

A well known advantage of spreading schemes is the possibility to infiltrate large quantities of water at relatively low costs. Also clogging problems are relatively easy to mitigate through construction techniques or operational procedures. Infiltration basins are probably the most favored method of recharge, because they allow efficient use of space, they can be integrated into a site's landscaping or open space, and require only simple maintenance. A disadvantage of water spreading schemes is the requirement of a large surface zone with an unconfined aquifer for infiltration, which is not always available.

Attributes overview

Attribute	Description
Use	All productive uses
Management purpose	Strategic storage, combat seawater intrusion
Scale	From small (community based) to large systems for city water supply
Source of water	River , canal or reservoir sometimes treated waste water or storm run-off
Geology	Unconsolidated sediments

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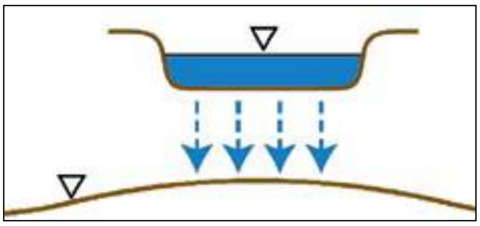
Hofkes E.H., Visscher J.T. 1986. Artificial Groundwater Recharge for water supply of medium-size communities in developing countries. *International Reference Centre for Community Water Supply and Sanitation. The Hague, The Netherlands.*

Pictures and drawings

Infiltration pond, Atlantis, South Africa

Schematic drawing of infiltration pond



Induced bank infiltration

Bank infiltration schemes commonly consist of a gallery or a line of boreholes at a short distance from, and parallel to the bank of a surface water body. Pumping of the boreholes lowers the water table adjacent to the river or lake, inducing this water to enter the aquifer system. During the passage of water through the riverbed (or lake bottom) and aquifer, dissolved and suspended contaminants as well as pathogens are removed due to a combination of physical, chemical, and biological processes. Induced bank infiltration systems are typically installed near perennial streams and lakes that are hydraulically connected to an aquifer through the permeable, unconsolidated deposits that form the stream bed or lake bottom.

Main application technologies

A large variety of schemes has been designed according to site-specific conditions. Collection wells can have either vertical or horizontal screens, depending on the thickness of the aquifer. Where aquifer material beneath a stream is thin, collector wells or infiltration galleries can be installed at the base of the aquifer to allow greater recharge of the aquifer than would otherwise be possible. Some induced bank infiltration schemes have been supplemented with infiltration ponds or recharge shafts to improve water quality and increase recharge. An artificial deposit can be applied to the riverbed, creating a reduced environment to prevent pollution of infiltrated water by organic material.

A special case of induced bank filtration is applied in the Netherlands, where small canals are used to manage and control groundwater levels in low lying parts of the country.

General features

River bank (and lake bank) filtration is applied as a source for drinking water production in Europe for more than a hundred years. Since 1950, increased contamination of surface waters with persistent organic compounds threatened the use of bank filtration. However in recent years, due to the success of effective control measures and a decrease in industrial pollution together with installed monitoring programs, bank filtration has again become a reliable resource for raw water abstraction.

Induced bank infiltration is practiced on different scales, but generally they are complex, large scale and high cost projects. In the Rhine basin alone, more than 20 million inhabitants receive drinking water which is directly or indirectly prepared from river water, mostly via bank filtration. At a smaller scale bank filtration is used for rural and small town water supply, also in developing countries. Bank infiltration schemes are usually managed by (municipal) water authorities.

The biggest advantages of induced bank infiltration schemes are that large amounts of groundwater may be abstracted from wells or galleries without serious adverse effects on the groundwater table further inland. Also particles, bacteria, viruses, parasites and easily biodegradable compounds are removed, and concentrations of persistent organic contaminants and heavy metals reduced in the filtration process.

Disadvantages are that the surface may need to be scraped during periods of low water level, if clogging of the river or lake-bed is excessive. Long term contamination of river water by persistent organic compounds (such as pesticides and pharmaceuticals) may contaminate the groundwater, and is therefore currently the biggest threat to induced bank filtration schemes.

Attributes overview

Attribute	Description
Use	Public water supply
Management purpose	Quality improvement, groundwater level control
Scale	From single abstraction well to large scale (Berlin, Budapest)
Source of water	Perennial river water, lake water
Geology	Unconsolidated sediments

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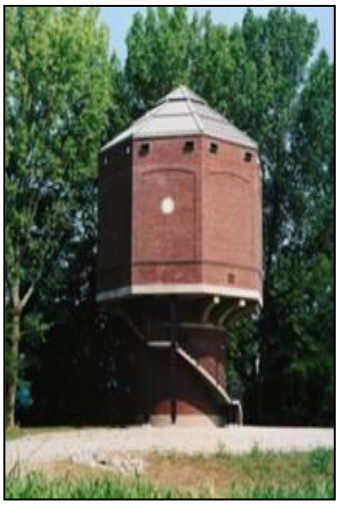
www.bankfiltration.org

Pictures and drawings



Wells, shafts and boreholes

In most cases, wells and boreholes are designed to withdraw groundwater from an aquifer. However, these structures can also be used to recharge the groundwater, a concept that is becoming increasingly popular throughout the world. There are two main types of groundwater recharge through wells, which can be distinguished by the depth of the aquifer that is being recharged.

Main application technologies

- Shallow depth well recharge: open wells and shafts are used to recharge shallow phreatic aquifers, and locations where surface layers are of low permeability and spreading methods are not effective. Wells that have run dry, due to falling water tables resulting from over-exploitation, are increasingly being used for this purpose. A problem associated with the use of these structures is the potential to introduce not only suspended solids, but also organic compounds (nitrates, pesticides) and bacterial contaminants directly into the aquifer. The use of existing structures is advantageous because it reduces costs.

  Recharge pits and trenches are used to infiltrate water into formations of good permeability which are not overlain by an impervious layer, or which are at trenchable depth (approximately 5 to 15 m). In general, pits and trenches are expensive to build and recharge small volumes of water. Therefore their use is mostly limited to those cases where they are already available in the form of abandoned quarries, gravel pits, etc.

- Deep well recharge is a relatively recent development, started around 50 years ago, when the first investigations of injecting potable water into saline aquifers were carried out. Deep well recharge is used where thick, low permeability strata overlie target aquifers, in order to recharge water directly into the aquifer. There are two typical applications:
  - Aquifer Storage and Recovery (ASR), where the well is used for both injection and recovery of water. ASR has become one of the most popular and commonly used deep well recharge techniques. Most operating ASR sites are storing treated drinking water to provide drinking water to cities and communities, especially in times of peak demand. In many cases, the storage zones are aquifers that have experienced long-term declines in water levels due to heavy pumping to meet increasing urban and agricultural water needs. Groundwater levels can then be restored if adequate volumes of water are recharged.
  - Aquifer Storage Transfer and Recovery (ASTR) involves water injection through a borehole, and recovery from another, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer.

General features

Design of recharge wells can vary considerably and include the construction of boreholes in the base of wells and backfilling the well with graded filter material to restrict ingress of suspended solids that would rapidly clog the system, and restrict inflow of contaminants. Recharge wells are advantageous when land is scarce. However, recharge water quality requirements are usually significantly higher for borehole injection than for groundwater recharge by means of surface spreading.

Advantages of ASR wells are that costs are minimized and clogging is removed during the recovery cycle. ASR systems can usually meet water management needs at less than half the capital cost of other water supply alternatives. However, to successfully apply ASR, extensive research and ASR pilot testing is needed, to evaluate permeability of aquifers, chemical changes in aquifer, the quality of recovered water, the efficiency of schemes and environmental impact.

Attributes overview

Attribute	Description
Use	Mainly domestic and industrial use, also for non-productive uses
Management purpose	Combat over exploitation and seawater intrusion
Scale	From single wells to well fields of 5-10 wells
Source of water	Lakes, streams, treated waste water, other aquifers, etc.
Geology	Unconsolidated sediments

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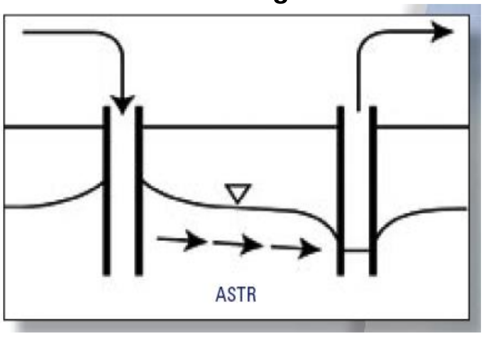
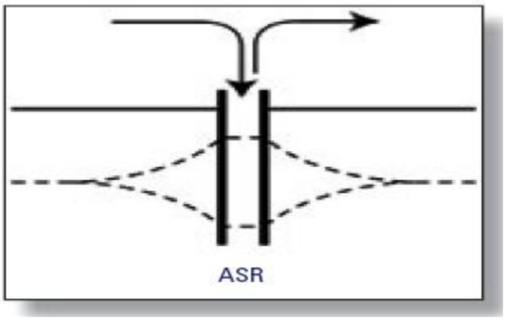
Pictures and drawings





Deep well infiltration (USA)

ASR well; Australia

Well infiltration, India

Recharge pit, Rajasthan, India ASR

In-channel modifications

In-channel modifications are structures that intercept or detain the stream flow through a natural drainage channel, and enhance the natural groundwater recharge. In-channel modifications are amongst the oldest AR techniques in existence. Dams built of stone rubble, dating back as far as the 3rd millennium B.C. have been discovered in Baluchistan and Kutch in India. In-channel modifications are predominantly used in arid regions, built across streams and sandy riverbeds that are seasonally dry. Generally, the purpose is to enhance groundwater recharge by storage of flood events and a controlled release, in order to facilitate its infiltration to the subsurface. A variety of in-channel structures are applied throughout the world:

Main application technologies

- Groundwater recharge dams are built in a streambed, and designed to collect stream runoff water in a surface water reservoir upstream of the dam. To provide recharge to groundwater, either the surface water reservoir upstream of the dam serves as a percolation pond, or water is released through pipes to infiltrate in the downstream riverbed.
- Subsurface dams refer to structures designed to contain underground flow, from a natural aquifer or from an artificial one, built with an impermeable barrier. It creates an area of groundwater storage upstream of the dam, raising the water table.
- Sand storage dams are constructed above ground in an ephemeral river bed. During periods of high flow, sand and gravel accumulates against the dam. Runoff water can easily infiltrate these highly permeable soil deposits, creating an artificial aquifer upstream of the dam.
- Mini-earthen check dams and permeable rock dams are gullies and ravines are transformed into small streams at the base of hills and divide the agricultural and non-agricultural land in to various segments. These streams are converted into series of mini water reservoirs by constructing check dams.
- Channel spreading techniques increase the wetted area and infiltration rate. Widening, leveling, scarifying and dredging of streambeds are all examples of this technology. Using "L"-shaped levees, the pattern of the surface flow in the river channel is changed, slowing the rate of river flow and increasing the channel length to provide more time for infiltration.
- Stream flow augmentation is a special case, which involves application of recharge water to a stream channel near the head of its drainage area to re-establish or increase infiltration through the stream bed. It is considered a recharge alternative in areas where streams fed by groundwater have ceased to flow of have become dry in their upper reaches.

General features

Although in-channel modifications all serve roughly the same purpose, each different technique has its own set of preferred geological conditions and streambed characteristics, which determine the applicability and probability of success at a certain location. Design of in-channel structures and construction materials used are dictated mainly by economic considerations, since it is technically feasible to construct these structures from almost any material. Because in-channel structures are applied at widely varying scales, from small structures with a length of a couple of meters up to large dams with a length of 9 km (Oman), they are constructed and managed on all levels, from individual farmers to water authorities and governmental institutions.

A big advantage water stored in a artificial aquifer upstream of a dam is that in semi-arid regions, clean potable water is available to local inhabitants in times of drought. In-channel modifications do not interfere with land use and have minimal impact on inhabitants and on the ecosystem.

Attributes overview

Attribute	Description
Use	All productive uses
Management purpose	Strategic storage
Scale	From small (check dams and sand storage dams) to large (recharge dams)
Source of water	Rainwater , surface run-off and stream run-off
Geology	Mainly in hard rock areas

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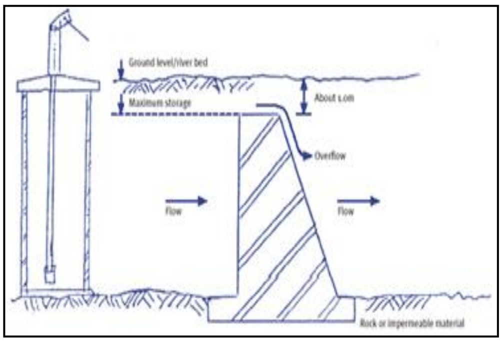
Pictures and drawings

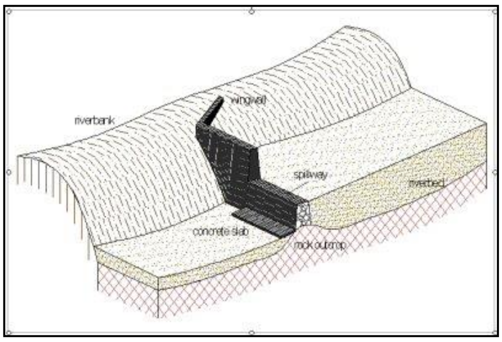
recharge dam

check dam (India)



schematic drawing of subsurface dam

construction of subsurface dam



schematic drawing of sand storage dam

sand dam (Kenya)

Rainwater Harvesting

Rainwater harvesting, in its broadest sense is the collection of runoff for productive use. It usually involves the concentration of rainfall from a larger area for use in a smaller area as soil moisture or for recharging groundwater. There are two main types of rainwater harvesting systems:

Main application technologies

- Roof-top rainwater harvesting is a special case being increasingly used in urban areas for tank storage, urban irrigation and groundwater recharge. Rainwater from roof-tops is collected and conserved for either direct consumption or for recharge. The main purpose of recharging is to increase groundwater storage for times when it is needed. Advantages of collecting and storing rainwater in urban areas include the demand reduction on water supply systems as well as reducing the amount of storm-water runoff and consequent flooding
- Ground surface runoff collection systems represent a broad variety of techniques, which all aim to obstruct surface runoff from catchments and concentrate the water to be stored in the soil profile or the deeper aquifer. Whichever system is used, the aim is to significantly reduce surface runoff and evaporation in order to enhance groundwater recharge. In most cases, the purpose of ground surface runoff collection systems is to enhance agricultural production by recharging the groundwater and, as an added benefit, reduce soil erosion. These systems are perhaps the most widely applied of all artificial recharge techniques:
    - *Barriers protruding from the ground surface*: Barriers act as an obstruction to overland water flow on hill slopes. The barrier reduces flow velocity and water percolates behind it, increasing soil moisture and recharging the groundwater. The most commonly used barriers are bunds and ridges, which are small stone or earthen walls, usually constructed along the contour. Barriers are generally applied in arid regions where runoff is sporadic but intense, generating high surface runoff
    - *Infiltration trenches, ditches and pits*: After periods of high rainfall, overland flow on hill slopes can be trapped in these structures. These man-made depressions in the hill slope will catch the runoff water and infiltrate it through the bottom and walls, thus recharging the groundwater and/or increase soil moisture. Infiltration trenches, ditches and pits are very adaptable, and are available in many practical configurations.

General features

The distance between barriers or trenches, their size, grade, etc., depend primarily on soil and subsurface conditions, which can vary considerably from place to place. One of the prime factors determining the applicability of these techniques is the slope of the area. Areas having slope greater than 5% are not recommended. Another factor is the soil. If the rainfall is less than infiltration rate in sandy soil, then the technique cannot be applied. Regular maintenance of schemes is required to prevent breaching of barriers and loss of permeability in trenches.

Although small-scale runoff collection activities can be organized on an individual farm basis in some locations, where many farms are found on steep slopes, effective programs will require an organized community effort, possibly with NGO assistance. In the past some large scale runoff collection and soil protection programmes have been initiated and funded by governments and international donors.

Advantages of ground surface runoff collection systems are that they prevent soil erosion as well as recharging the groundwater. Also systems collecting surface runoff from fields are cheap and easy to construct. However, the volumes of recharged water are relatively small, and benefits may not be visible for years.

Attributes overview

Attribute	Description
Use	Domestic and agricultural water supply
Management purpose	Strategic storage , erosion control
Scale	Usually small
Source of water	Rainwater and surface run-off
Geology	Unconsolidated sediments

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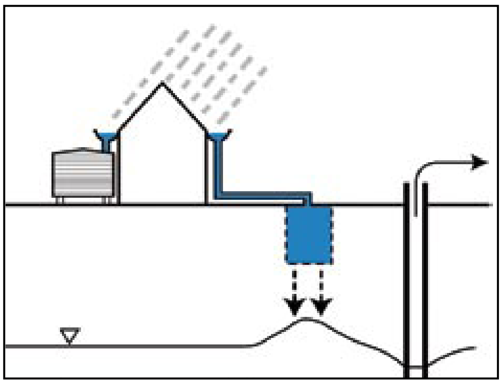
Pictures and drawings

Contour bunds

Trenches



Schematic drawing of system using roof top rainwater for groundwater recharge

Case-study spreading techniques

General information

1. Name:

Infiltration pond South Africa

2. Picture:

Figure 1: Infiltration pond in dunes in Atlantis, South Africa. (Source: Tuinhof A.)

Figure 2: Map of Atlantis artificial recharge scheme. (Source: Tredoux G. 2002).

3. Brief description of the situation:

The town of Atlantis, located 50 km north of Cape Town, was fully dependent on groundwater at its inception in 1976. However, groundwater supplies are limited and artificial recharge through infiltration basins was introduced shortly afterwards for augmenting local groundwater supplies (Figure 1).

Being a new development, the town was planned with fully separated residential and industrial areas. This fact contributed to the success of the artificial recharge operation, as diversion of stormwater and wastewater flows of inferior quality from the industrial area was possible (Figure 2). Since 1999, the scheme was augmented with a limited supply from surface water sources to meet peak demands, but the town is still mainly dependent on the local groundwater. The city of Atlantis has over 100 000 inhabitants, and water consumption without restrictions is around 7 Mm3/year (in 1999 and 2000).

Atlantis is located along the semiarid west coast of South Africa. Most of the 450mm mean annual rainfall is received from April to September. As a result of the sandy surface over most of the area, recharge percentages of 15 to 30% of the annual rainfall are generally experienced, the higher recharge occurring in the unvegetated dune area.

Technical information

4. Brief description of the technique:

Infiltration ponds are used to infiltrate water into formations of good permeability, which are not overlain by an impervious layer. Ponds are either excavated, or are enclosed by dikes or levees which retain the recharge water until it has infiltrated through the floor of the basin.

In the Atlantis area, minimal runoff is generated under natural conditions due to the high infiltration capacity of the soil. It was realized that large volumes of stormwater runoff would be generated after urbanization and the associated hardening of surfaces. This was seen as a valuable water source for augmenting freshwater supplies in this region, and prompted the construction of a stormwater collection system. As an added water source, treated domestic waste water is recharged to the aquifer along with the stormwater.

5. Attributes overview:

Attribute	Description
Use	Domestic water supply
Management purpose	Strategic storage, water quality improvement
Scale	Large
Source of water	Urban stormwater and wastewater
Geology	Unconsolidated sediments

6. Construction:

The system consists of twelve detention and retention basins and the necessary interconnecting pipelines with peak flow reduction features.

- Low salinity flows are channeled into two large spreading basins for subsequent infiltration in the Witzand aquifer, upgradient of the Witzand wellfield.
- Higher salinity baseflow is diverted to the coastal basins or to the Donkergat river.
- A weir in the stormwater system separates the slightly more saline baseflow from the low salinity peak flow. Domestic and industrial wastewater is treated separately in twin wastewater treatment works. Only the final effluent from the domestic works is used for recharge upgradient of the Witzand wellfield
- Treated industrial wastewater, softening plant regenerant brine, and industrial area stormwater is discharged into the coastal recharge basins. In doing so, a steeper hydraulic gradient is created near the coast, which may help to reduce the outflow of good quality groundwater, as well as reduce the risk of seawater intrusion into the Witzand unit.
- Ponds are generally 1-4 m deep, which is enough to prevent excessive growth of algae or water plants, and shallow enough to prevent anaerobic conditions developing except at the bottom.

7. Capacity:

Discharges during storm events can reach up to 72 000 m3/day at Atlantis, while summer baseflow averages 2160 m3/day (Wright, 1994). The baseflow is mostly groundwater entering the stormwater pipelines in areas where these are below the water table.

Stormwater and wastewater infiltration augments the natural recharge of the groundwater in the Witzand unit by 1.5 to 2.5 Mm3/year.

Infiltration of treated industrial wastewater, softening plant regenerant brine, and industrial area stormwater, is together exceeding 2 Mm3/year.

The accepted abstraction capacity for the Witzand wellfield is 5 Mm3/year, and for the Silwerstroom wellfield is 1.8 Mm3/year. This means that about 30% of the abstracted water from the Witzand wellfield derives from artificial recharge.

8. Experiences with Operation and Maintenance:

Maintenance of the recharge structure is important. The bottom of the pond must be inspected and treated regularly in order to minimize clogging to maintain infiltration rates and keep evaporation from open water to a minimum.

Iron-related clogging of abstraction boreholes due to overpumping of the boreholes has proven to be an extensive and serious problem. From 1999 to 2002, boreholes were examined and rehabilitated using special treatment techniques.

9. Experiences with Monitoring and Evaluation:

Managing water quality and, in particular, salinity has been one of the greatest challenges for the Atlantis Water Scheme. Management actions to control salinity in the Atlantis water supply have included the launching of a detailed chemical investigation of the salinity sources. Regular monitoring takes place around the recharge and abstraction areas and at potential pollution sources. This also provides an early warning system against any potential uncontrolled spills and illegal discharges of harmful contaminants.

Improved environmental practices have been initiated by some of the industries. These have resulted in the commissioning of site assessments and in some cases the initiation of groundwater monitoring programmes. Increased understanding of their contamination threats allows these industries to improve their operating procedures to protect their water resource.

10. Experiences with related subjects (e.a. erosion prevention, quality of drinking water):

Water quality: As water migrates through porous soil and rock, pollutant attenuation mechanisms include precipitation, sorption, physical filtration, and bacterial degradation. If functioning properly, this approach is presumed to have high removal efficiencies for particulate pollutants and moderate removal of soluble pollutants.

In Atlantis, the Witzand unit is separated from areas with poorer groundwater potential (where also the noxious industries of Atlantis are located) by high bedrock, which acts as a groundwater divide.

Financial information

11. Experiences with management:

The artificial recharge system at Atlantis is a complex, large schale scheme. The system has been managed by the Water Department of the City of Cape Town and its predecessors, the Cape Metropolitan Council, the Western Cape Regional Services Council and the Cape Divisional Council.

12. Benefits:

The inhabitants of Atlantis (> 100 000) have access to good quality drinking water in a semi-arid region with little surface water resources.

General conclusions

13. Generic factors of success and traps ('do's and don'ts'):

- A detailed analysis of rainfall pattern, number of rainy days, dry spells, and evaporation rate and detailed hydrogeological studies should be undertaken to demarcate suitable percolation tank sites.
- During construction of the basin, driving heavy equipment over the infiltration surface should be avoided if possible.
- Scheduling basin "rest" periods of sufficient duration between flooding periods allows drying and biodegradation of clogged layers. Periodic deep ponding increases basin heads to overcome surface clogging.

14. What can be used elsewhere, under which conditions:

Infiltration ponds recharge the groundwater in an aquifer by infiltration of water stored in the pond through the bottom of the pond. Therefore percolation ponds can be applied almost anywhere, provided that there is a supply of clean fresh water available at least part of the year to fill the pond, the bottom of the pond is permeable, and the aquifer to be recharged is at, or near the ground surface. Infiltration ponds require a relatively large surface area for spreading. Therefore ponds are only suitable where there is ample room for installation. Because infiltration ponds are very vulnerable to contamination, they should be located in protected areas.

15. Advantages and disadvantages:

Advantages	Disadvantages
Expected flows can be accommodated by constructing basins of appropriate size. Intermittent floodwater can be stored for later infiltration. Clogging can be mitigated through proper basin construction techniques or operational procedures. Because infiltration basins are equipped with an intake system, intake can be stopped during periods when the water source is of poor quality. They are integrated into the site's landscape.	Not suitable on fill sites or slopes. Risk of groundwater contamination in very coarse soils. Storage of surface water may increase breeding of surface water related disease vectors, and concomitantly increase the risk of diseases, such as malaria.

16. Links to detailed information of this project / technique:

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Tel: 021 888 2591
Cell: 082 940 6147

17. References

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Case-study: Induced bank infiltration

General information

1. Name:

Induced bank infiltration Hungary

2. Picture:

Figure 1: Danube river in Budapest, Hungary. (Source: Sándor, 2005)

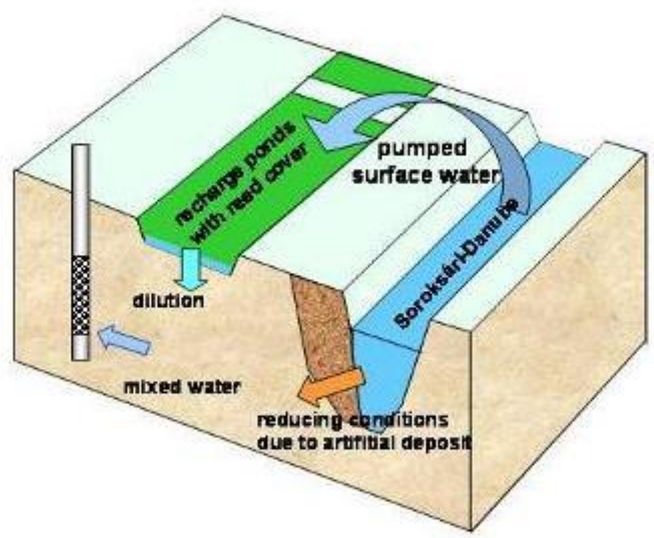

Figure 2: Schematic drawing of Induced bank filtration at the Szigetszentmiklós wellfield. (Source: Simonffy Z. 2002).

3. Brief description of the situation:

Hungary is located in the deepest part of the Carpathian basin. The majority of surface water arrives from the surrounding countries. Three large rivers leave the country after collecting the Hungarian runoff, which is the smallest in Europe and only adds 5% to the total outflow of these rivers. Potential evapotranspiration exceeds the precipitation from April to October, and consequently the runoff in summertime, when the peak of water demand occurs, is very low. Furthermore, the relief of the country is not very favourable for reservoirs.

These conditions have resulted in the present situation, where 70% of the total abstraction in Hungary is from groundwater. Abstraction of groundwater for public use even amounts to 94% of the total abstraction. This leads to a high pressure on the groundwater resources.

Induced bank infiltration is an artificial recharge technique that offers a mitigation measure to these issues. More than one third of the total Hungarian groundwater abstraction for public use is being supplemented by induced bank infiltration. The drinking water supply of Budapest completely relies on this type of resource.

This case study describes the induced bank infiltration system installed at Csepel Island, Budapest (Figure 1). It is one of the two induced bank infiltration systems supplying drinking water to the 1.7 million inhabitants of Budapest. The Csepel island can be found downstream of Budapest. Because there is a potential pollution hazard related to wastewater from the city of Budapest, the situation is more sensitive than at other induced bank infiltration sites in Hungary. The island consists of a sandy-gravely deposit which is very suitable for bank infiltration. The coarse material offers a very high permeability, while the fine sediment of the riverbed provides an efficient natural filter for the infiltrating surface water.

Technical information

4. Brief description of the technique:

Bank infiltration schemes commonly consist of a gallery or a line of boreholes at a short distance from, and parallel to the bank of a surface water body. Pumping of the boreholes lowers the water table adjacent to the river or lake, inducing this water to enter the aquifer system. During the passage of water through the riverbed (or lake bottom) and aquifer, dissolved and suspended contaminants as well as pathogens are removed due to a combination of physical, chemical, and biological processes. Induced bank infiltration systems are typically installed near perennial streams and lakes that are hydraulically connected to an aquifer through the permeable, unconsolidated deposits that form the stream bed or lake bottom.

5. Attributes overview:

Attribute	Description
Use purpose	Domestic water supply
Management purpose	Groundwater storage control
Scale	large scale
Source of water	Perennial rivers
Geology	Unconsolidated sediments

6. Construction:

- The wells are placed on an island, to allow for abstraction of a high portion of bank filtrate. Wells are grouped into galleries and oriented parallel to the river bank.
- The thickness of the aquifer ranges between 3 and 15 m. Because the gravel terrace is not very thick at some locations, exploitation of these sections of the aquifer would require a lot of traditional tube or shaft wells. Therefore special large shaft wells with horizontal screens have been constructed here.
- At other locations on Csepel island, such as the Szigetszentmiklós wellfield, bank filtration is combined with artificial recharge from infiltration ponds (Figure 2). This is done to improve the water quality.
- The distance between wells in this system and the river bank ranges between 5 and 100 m. The proximity of wells to the river bank, in combination with the high permeability of the aquifer, results in very short travel times of the river water to the wells.

7. Capacity:

System capacity of the Csepel Island bank infiltration system is 400 Mm3/day, or 146 Mm3/year. The actual abstraction in 2002 was 250 Mm3/day, or 91 Mm3/year. This is contributing 40% of the drinking water supply to Budapest. The extra capacity of the system is designed to allow for increased abstraction in the future. The capacity of the shaft wells with horizontal screens is ranging between 10 – 20 Mm3/day.

8. Experiences with Operation and Maintenance:

At Szigetszentmiklós wellfield, the bank-filtered water is moving through an artificially made bank, constructed of dredged sediment from the Danube. Because the dredged sediment contains a relatively high content of organic material the water is reduced, and consequently high iron and manganese content can be present in the wells. As active protection, recharge ponds have been constructed between the bank and the wellfield. These ponds infiltrate water pumped from the Danube, providing sufficient dilution with the bank filtered water in the aquifer. The reed cover of the infiltration ponds has been found very efficient to maintain a high infiltration capacity.

9. Experiences with Monitoring and Evaluation:

Monitoring is showing that although the travel time is very short, the bank filtered water does not need other treatment than disinfection. The natural filtration capacity of the exploited river sections are very efficient, no micro-pollutants have been found in he abstracted water. Because travel times are short (ranging between 5 and <1000 days), monitoring is especially important to ensure the good quality of the water abstracted from the wells.

10. Experiences with related subjects (e.a. erosion prevention, quality of drinking water):

Water quality: An international commission for the protection of the river Danube was founded in 1994. The activities of this commission, together with the activities of waterworks, authorities, industries and transboundary programmes, resulted in a significant improvement of river water quality. In Budapest, drinking water is being continuously tested and is of good quality.

Financial information

11. Experiences with management:

Induced bank filtration systems are complex, large scale and high cost projects. The Csepel bank infiltration is managed by the water authorities of Budapest, and funded by the state.

12. Benefits:

The Csepel island induced bank filtration system is an expensive large scale system, involving a high number of wells. However, the large quantities of water abstracted from the wells allow for a relatively low unit price of water. Because the bank filtered water is already of good quality, the water does not need other treatment than disinfection. This also aids in keeping the unit price of water abstracted here relatively low.

General conclusions

13. Generic factors of success and traps ('do's and don'ts'):

If aquifer thickness is small, horizontal well screens allow for high abstraction rates without the need for larger and more expensive wellfields using traditional vertical screens.

14. What can be used elsewhere, under which conditions:

Induced riverbed infiltration systems are typically installed near perennial streams that are hydraulically connected to an aquifer through the permeable, unconsolidated deposits that form the stream channel. The quantity of surface water that can be induced to recharge the aquifer varies with:

- Amount and proximity of surface water
- Hydraulic conductivity of the aquifer
- The area and permeability of the stream bed (or lake bottom)
- The hydraulic gradient created by pumping

Silt deposition, the primary cause of decreased stream bed permeability, can be avoided by placing pumping facilities near stream reaches having adequate velocity to prevent deposition, such as the outer edge of a bend in the stream.

15. Advantages and disadvantages:

Advantages	Disadvantages
The possibility to extract large volumes of water is the biggest advantage. The abstracted amount is limited by the infiltration capacity of the river bank only, because the discharge of the river is an order of magnitude greater than the abstracted amount.	Long term contamination of river water by persistent organic compounds (such as pesticides and pharmaceuticals) may contaminate the groundwater.
Compared to surface water abstraction, the treatment requirements of the water are reduced. The natural filtration capacity of the exploited river sections in Budapest is very efficient, and no micro-pollutants have been found in the abstracted water.	

16. Links to detailed information of this project / technique:

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17. References:

Grischek T., Schoenheinz D., Worch E. 2002. Bank filtration in Europe – An overview of aquifer conditions and hydraulic controls. Management of Aquifer Recharge for Sustainability. Proceedings of ISAR-4, Adelaide, South Australia.

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Simonffy Z. 2002. Enhancement of groundwater recharge in Hungary – 'Bank infiltration or drinking water supply'. Management of Aquifer Recharge and Subsurface Storage. NNC-IAH publication #4. Utrecht, The Netherlands http://siteresources.worldbank.org/INTWRD/Resources/GWMATE_Final_booklet.pdf

Case-study well, shaft and borehole recharge

General information

1. Name:

ASR (Aquifer Storage and Recovery) wetlands (Australia)

2. Picture:

Figure 1: ASR well at Parafield ASR project site, Australia (Source: Dillon P. 2005)

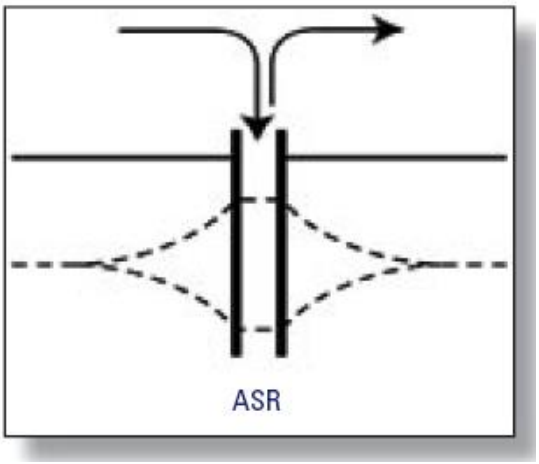

Figure 2: Schematic drawing of ASR system. (Source: Gale I. 2005)

3. Brief description of the situation:

South Australia is the driest state in Australia, which in turn is the driest inhabited continent on earth. Access to cheap, good quality water is one of the critical issues facing the development of the State. In the past, storm water and sewerage effluent has always been channeled to the coast, where it has degraded the marine environment. Water for utilization has always been pumped from River Murray, a river that is undergoing an ecological crisis through over use and mismanagement.

The city of Salisbury, located 25km north of Adelaide in South Australia, is nowadays an international leader in the use of wetlands and ASR technology for stormwater management and utilization. Stormwater, traditionally regarded as a problem, and in some cases a threat, is now harnessed and utilized by Salisbury in a series of wetlands, enhancing the landscape and creating habitat diversity.

The Parafield stormwater treatment and reuse project is one of the most recent and most challenging of the Salisbury wetlands projects. Urban stormwater is harvested at Parafield airport, treated, and injected into a formerly brackish limestone aquifer to provide low salinity water supplies for industrial use and irrigation in Salisbury (Figure 1). This project is described in more detail here.

Technical information

4. Brief description of the technique:

Aquifer storage and recovery (ASR) may be defined as the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed (Figure 2).

Design of structures can vary considerably and includes the construction of boreholes in the base of wells and backfilling the well with graded filter material to restrict ingress of suspended solids that would rapidly clog the system, and restrict inflow of contaminants.

5. Attributes overview:

Attribute	Description
Use	Industry, ecology and environment, and to a lesser degree agriculture.
Management purpose	Quality improvement
Scale	large
Source of water	Urban stormwater
Geology	Limestone

6. Construction:

Urban stormwater is guided through several components. First the stormwater is harvested and diverted from existing drains to a constantly flowing system of, bird-proofed reed bed ponds. Then the water is stored in a capture basin. From there it is pumped to a similar capacity holding basin, from where it is gravitated to a two hectare cleansing reed bed. Water will then flow continuously through the densely planted reed bed to biologically cleanse the water. After cleansing and filtering, the water is supplied directly to users. Surplus water is injected into a formerly brackish limestone aquifer via

ASR-wells, to provide low salinity water for extraction during dry periods. The ASR wells are drilled to depths between 160 to 180 m.

7. Capacity:

The scheme capacity for both the direct supply to users and the ASR extraction is 1.1 Mm3/year in the first stage. A proposed second stage of the Parafield scheme will expand minimum yield to 2.1 Mm3/year by adding other catchments. Use of the water will be facilitated by the development of an ASR borefield.

- Injection rate is 35 l/s
- The total catchment area from which stormwater is harvested is 1600 ha.
- The system is designed to provide an average of 10 days of residence time for the stormwater in order to ensure optimal treatment efficiency.
- The flood protection ratio is 1 in every 10 years.

8. Experiences with Operation and Maintenance:

In general, design of ASR-structures can vary considerably and include the construction of boreholes in the base of wells and backfilling the well with graded filter material to restrict ingress of suspended solids that would rapidly clog the system, and restrict inflow of contaminants. Clogging of aquifer material or the borehole screen can be managed by:

- Mechanical and/or chemical treatment of recharge water
- Introduction of water through a valve to ensure a continuous column to the surface
- Regular recovery using surging and pumping

9. Experiences with Monitoring and Evaluation:

At Parafield, flow rates, pressures and water quality are automatically monitored and linked to a programmed control system with telemetry to council offices. Online monitoring is performed on pH, TDS, and SS.

10. Experiences with related subjects (e.a. erosion prevention, quality of drinking water, ..):

Water quality: At the Parafield site, nutrient and pollutant loads will be reduced by up to 90% and the treated water has a salinity of <250 mg/L.

Financial information

11. Experiences with management:

Over the last 20 years, the Salisbury Council has constructed more than 30 wetlands covering an area of 260 hectares and costing in excess of US$ 14 million. The Parafield site is one of the most recent of these wetland areas.

12. Benefits:

The costs of the first stage of the Parafield project are US$ 2.9 million. Benefits include the harnessing and utilization of stormwater (traditionally regarded as a problem), enhancing the landscape and creating habitat diversity. The ASR system provides low salinity water supplies for industrial use and irrigation in Salisbury.

General conclusions

13. Generic factors of success and traps ('do's and don'ts'):

To successfully apply ASR, extensive research and ASR pilot testing is needed, to evaluate permeability of aquifers, chemical changes in aquifer, the quality of recovered water, the efficiency of schemes and environmental impact.

14. What can be used elsewhere, under which conditions:

ASR is used where thick, low permeability strata overlie target aquifers. Recharge wells are also advantageous when land is scarce. Ideally, ASR sites should be located in a confined, single porosity aquifer at sufficient distance from the outcrop to have an acceptable impact on flows in streams. A readily accessible source of water for injection is needed and access to an existing treatment works could be important if the recovered water is not wholly potable. ASR can be applied to saline or brackish aquifers. This is possible when the potable injection water displaces, rather than mixes with, the natural water. Some mixing on the fringes of the stored water does take place and reduces the quality of some of the recovered water.

15. Advantages and disadvantages:

Advantages	Disadvantages
Advantages of ASR wells are that costs are minimized and clogging is removed during the recovery cycle.	Recharge water quality requirements are usually significantly higher for borehole injection than for groundwater recharge by means of spreading.
ASR systems can usually meet water management needs at less than half the capital cost of other water supply alternatives.	The technology needed to construct ASR systems is complicated and costly.
	Detailed knowledge about subsurface is required for successful application of ASR

16. Links to detailed information of this project / technique:

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17. References:

Chaudhary H., Pitman C. 2002. Implemnting large scale stormwater recycling schemes – meeting economic, environmental and community objectives. Management of Aquifer Recharge for Sustainability. Proceedings of ISAR-4, Adelaide, South Australia.

Gale I. 2005. Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas. IAH – MAR, UNESCO IHP. Paris, France.

Pyne, R. D. G. (1995). Groundwater recharge and wells: A guide to Aquifer Storage Recovery. Florida, USA., CRC Press.

http://www.awwarf.org/research/topicsandprojects/execSum/713.aspx

http://www.wpb.org/utilities/cwmrp/asr.htm

Case-study: In-channel modifications

General information

1. Name:

Sand dam Kenya

2. Picture:

Figure 1: Sand dam in ephemeral stream bed in Kitui district, Kenya (Source: Borst & Haas, 2006)

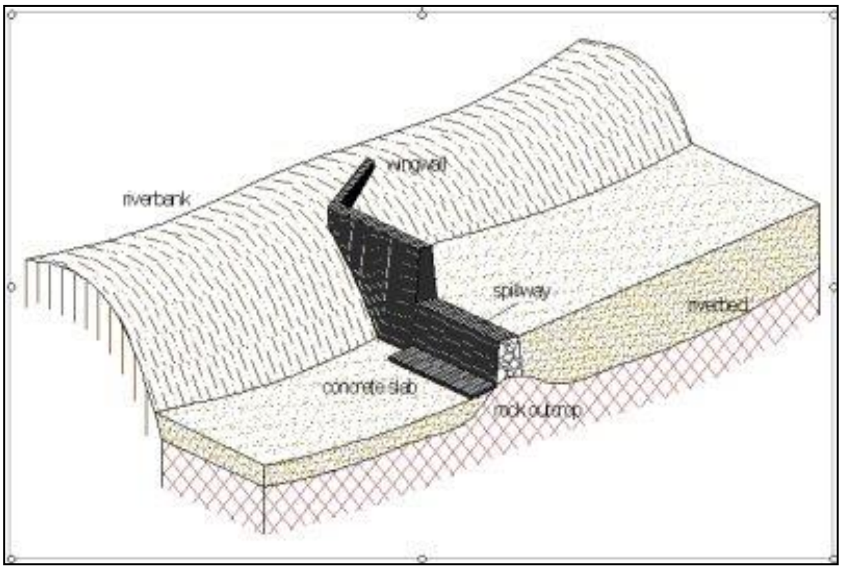

Figure 2: Schematic cross-section of sand dam (Source: Borst & Haas, 2006).

3. Brief description of the situation:

Irrigation potential in South and East African countries is much higher than the presently irrigated area. A variety of soil moisture and water conservation technologies could be adopted to reduce the cost of irrigation, extend it throughout and promote sustainable small-scale irrigation on a watershed basis. These technologies are essential especially in drought-prone areas. Even though drought is a purely natural calamity caused by the failure of (monsoon) rain, it can be minimized by careful planning and operation. During good rainy years, excess rainwater should be stored in the soil and also underground using suitable soil moisture conservation measures and water harvesting structures on a watershed basis. This stored water can subsequently be used for irrigation.

An example of a rural water conservation programme is the construction of sand dams in the Kitui district in Kenya (Figure 1). This programme is a co-operation between the community and the Sahelian Solution Foundation (SASOL). SASOL, founded in 1990, assists Kitui communities to address household and production water scarcity through the sand dam technology.

Although the sand dam technology has been known for 3000 years since the time of the Babylonian Kingdom, it has not been applied at a large scale. This might be because it is a low-key technology and there is no grandeur to it. As a result its full capacity has not been realized and developed, even though it is one of the major systems to aid communities living in arid and semi arid lands with ideal condition for its application.

Technical information

4. Brief description of the technique:

The sand-storage dam is a small-scale concrete checkdam, constructed above ground in an ephemeral river bed (Figure 2). During periods of high flow sand and gravel accumulates against the dam. Runoff water can easily infiltrate these highly permeable soil deposits, creating an artificial aquifer upstream of the dam capable of recharging the groundwater and providing clean water if well harnessed. Sand accumulated against the dam can store up to 35 percent of its total volume as groundwater.

5. Attributes overview:

Attribute	Description
Use purpose	Domestic & Agricultural
Management purpose	Groundwater storage control
Scale	Small scale
Source of water	Rainwater , surface run-off and stream run-off
Geology	Hard rock areas

6. Construction:

The design and construction of sand dams is variable. Each site is different. Rivers vary in width and discharge, rock foundations vary in depth and susceptibility to leakage, riverbanks may be high or low. The location of a sand dam should be chosen such that: it is feasible on technical grounds, it has high storage capacity, it has minimum cost and it is convenient to the community using it. The selected location is excavated to reach a firm impermeable layer as founding layer for the dam. This layer may be base rock, clay or murram (coarse gravel with clay matrix) and is usually uneven.

The height of a sand dam is usually about 1.5 to 2 m in the centre, but some dams up to 4 m have been constructed. At either end the wall is raised to prevent the river cutting round during a flood. Where the valley sides are flat, wing walls may be added at an angle to the main dam for the same purpose. Normally the base width of a wall is 1.5 m and top width 0.75 m. The upstream side is vertical, the downstream side angled. In Kitui, Kenya, dams are made of masonry, because this is relatively cheap. Also masonry has a long lifetime and requires minimal maintenance.

7. Capacity:

The maximum amount of water that can be harvested per year from an average sand dam is around 5300 m3 (Alvarado, 2006) or 8100 m3 (Borst and Haas, 2006).

8. Experiences with Operation and Maintenance:

Sand dams are permanent structures with a long lifetime, provided they are well maintained. If a sand dam has been well constructed, there should be little or no maintenance. However, it is necessary to check after floods and repair any damage that is found. In the Kitui district in Kenya, sand dams built in the 1950s and 1960s continue to function to date.

9. Experiences with Monitoring and Evaluation:

In Kenya, SASOL Foundation has conducted a number of studies on their use and socio-economic benefits, supplemented with work carried out by students. A hydrological and socio-economic evaluation of existing dams implemented by SASOL, Acacia, IVM and the PWN with financial support from Aqua4all has started in 2006. Some conclusions of this evaluation are:

- The dams fill rapidly during the floods and a substantial amount of additional water is stored in the riverbanks
- A preliminary water balance shows that only a minor portion of the total run-off water (<5%) is intercepted, indicating minor impacts on the downstream users.
- The occurrence of a serious drought during the period of investigations confirms that the dams provide water during drought periods.
- The socio-economic study shows a significant improvement on income and economic growth

10. Experiences with related subjects (e.a. erosion prevention, quality of drinking water):

Ecosystem regeneration: Where sand dams have been constructed, substantial regeneration of natural vegetation and ecosystem function is evident.

Water quality: The water is captured for use through a hand dug well or tube well that is put into the sand in the dry season. This water is clean and of good quality for consumption due to the filtering effect of the sand. Quality issues may develop from livestock drinking from scoop-holes, causing bacteriological pollution. Therefore it is recommended that abstraction wells are sited some distance upstream of the dam wall. Livestock may be allowed to drink from scoop-holes near the dam wall so that they do not pollute the surroundings of the well.

Financial information

11. Experiences with management:

The economic conditions in Kenya are such that participatory or bottom-up approaches are essential in the dam construction (and obtain maximum socio-economic benefits). Using locally available materials and community labour reduces costs and enhances efficiency, acceptance and dam life-span. Cost of an average dam in Kenya is about US$8,500. Some 40% of overall construction cost is provided by the community, resulting in community ownership and commitment to maintain the dam. The investment cost per consumer is about 5-10 US$.

12. Benefits:

In the Kitui region of Kenya, water is now available within short distances from homesteads and people have improved their livelihoods significantly by engaging in small-scale irrigation for growing food- and cash crops.

In the Kitui area, nearly 200,000 households have benefited through:

- cutting the average time spent on water collection
- increased crop production and better quantity and quality of drinking water-supply
- improving the hygiene and nutrition of people, livestock and poultry
- increased income

	Before dam construction	**After dam construction**
# of types of cash crops	1.5	2.8
% crops irrigated	37	68
Domestic water collection	140	90
Livestock water collection	110	50
Average walking distance to water	3	1
Income (US$/year)	230	350
% households suffering from malnutrition	31.6	0

Table 1: Measured social and economic impact of sand dams in the Kitui region, Kenya

General conclusions

13. Generic factors of success and traps (‘do’s and don’ts’):

The need for wing-walls and a spillway must be carefully assessed. In some cases it is considered preferable to construct the dam in layers. The idea is to keep a sufficiently high velocity in the reservoir so that light particles cannot settle and diminish the infiltation capacity of the accumulated material upstream.

Community involvement is essential for the success of sand dams. It is important that communities reach consensus on the initiation and benefits of new activities.

Dams can be built in cascade, providing water for the whole catchment area. Ecological damage on a single point water source is avoided and it is likely to get a higher rise in water table than in individual units. Recharge into soil storage spaces is hence much more effective.

Site selection is important. Errors in site selection may result in:

- insufficient storage potential
- insufficient depth to reach relatively impermeable bedrock
- location in soil types with very low infiltration capacity
- severe groundwater salinization

14. What can be used elsewhere, under which conditions:

This technique is applicable in sandy riverbeds that are seasonally dry but experience high siltation during water runoffs. Sites with high riverbanks and lower slopes are also desirable. River valleys and regions sloping between 1 and 2% are ideal sites for sand dams, as these normally give the highest water storage. An impermeable layer underneath the dam and the sandy aquifer is desirable, so that little water is lost to deeper aquifers and leakage at the dam is prevented. This technique is mostly applied in regions with semi-arid climates and erratic rainfall.

15. Advantages and disadvantages:

Advantages	**Disadvantages**
The main advantage of these dams is that they use simple inexpensive technology, and can be constructed by local communities mainly with locally-available materials.	Potential ownership issues may arise.
structures are installed in streambeds, and therefore do not interfere with land use.	Salinization may compromise water quality. Water quality may also be compromised through contamination by lifestock
	Because sand dams store water within the alluvial soil profile, their capacities are low compared with those of conventional dams. Yield is determined by the quality of sand and the surrounding soil properties.

16. Links to detailed information of this project / technique:

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17. References

Borst L. and Haas S.A. (2006). Hydrology of Sand Storage Dams, A case study in the Kiindu catchment, Kitui District, Kenya. Master thesis, Vrije Universiteit, Amsterdam.

Foster S. and Tuinhof A. (2005) Brazil, Kenya: Subsurface dams to augment groundwater storage in basement terrain for human subsistence. The world bank, Sustainable groundwater management.

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Thomas D.B. 1999. Where there is no water: A story of community water development and sand dams in Kitui District, Kenya. SASOL and Maji Na Ufanisi.

http://kenia.famvdhoeven.nl/downloads/SASOL_storage_dam_costs.pdf

Case-study runoff harvesting

General information

1. Name:

Teras (Sudan)

2. Picture:

Figure 1: Inspection of base bund as part of Teras water harvesting structure (Source: www.fao.org)

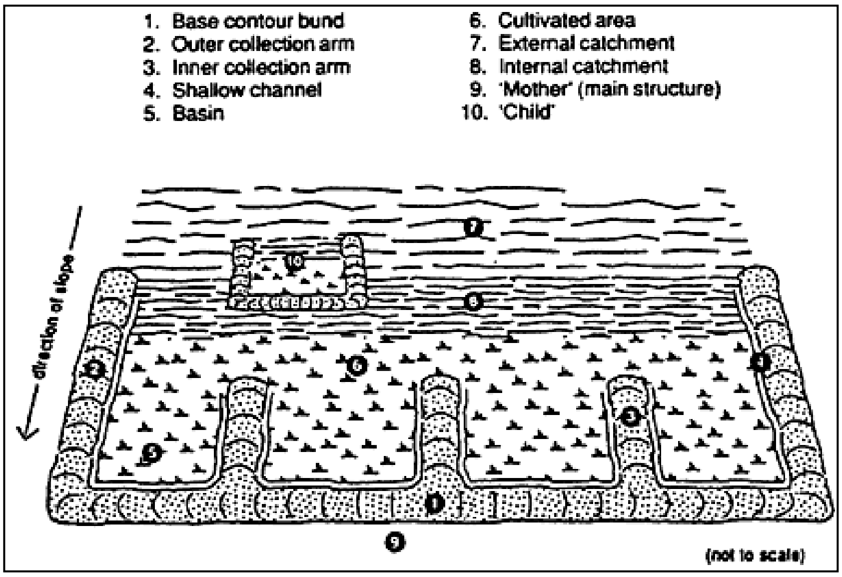

Figure 2. Typical elements of the Teras water harvesting structure (Source: Dijk J.A. van, 1995).

3. Brief description of the situation:

African drylands are vulnerable to food insecurity. Their populations grow rapidly, while most of the best soils for crop production are already being used. The resulting forced expansion into more marginal areas for cultivation results in land degradation, which further increases the hazard of food insecurity (Engelman and Leroy, 1995). In an attempt to halt this downward spiral, several new crop production systems have been introduced in recent decades. Attention is recently being given to building on indigenous knowledge (Warren, 1991). When indigenous techniques are improved, dissemination is usually faster, more widespread and cheaper because it fits better into local environmental and socio-economic niches (Reijntjes, et al., 1994).

Socio-economic data and remote sensing in the Border Area in eastern Sudan indicate that the use of indigenous soil and water conservation techniques (ISWC) is expanding. The most elaborate ISWC technique applied in eastern Sudan is the Teras system (bunded landholding, see Figure 1).

This case-study describes the use of the teras ISWC technique in the rural village of Ilat Ayot, near Kassala, eastern Sudan. More information about the Teras technique in other villages in this region is given by van Dijk, 1997.

Technical information

4. Brief description of the technique:

Bunds are small stone or earthen walls, usually constructed along the contour. Bunds act as an obstruction to overland water flow on hill slopes. The bund reduces flow velocity and water percolates behind it, increasing soil moisture and recharging the groundwater.

Teras is the name given to a landholding which is bunded on three sides (Figure 2). The fourth is left open to capture run-off from an adjacent, slightly elevated catchment. The Teras technique consists of a base bund which approximately follows the contour line and impounds the runoff. Two outer arms fulfill the same function and also act as conveyance structures which direct water to the cultivated lands. Sometimes, shorter inner arms are added which divide the land into smaller basins and improve the spread of captured runoff (Figure 15). A shallow channel is left on the inside of the bund to support the conveyance and circulation of runoff. Excess water is normally drained along the tips of the outer arms.

The Teras technique is applied to increase agricultural production, and does not directly increase drinking water supply.

5. Attributes overview:

Attribute	Description
Use	Agricultural water supply
Management purpose	Strategic storage , erosion control
Scale	Small
Source of water	Rainwater and surface run-off
Geology	Unconsolidated sediments

6. Construction:

Teras bunds are built by hand and are made of local alluvial and colluvial material. In the dryer northern parts of the Border Area, land users also erect brushwood to capture sand and dust in order to let bunds rise by wind action. The bunds are usually 0.5 m high and 2 m deep at the base, but these dimensions can vary greatly depending on both the slope and the amount of runoff expected in the area. The base can be between 50 to 300 m long, while the arms are usually 20 to 100 m long.

7. Capacity:

There are no data on the water storage capacity available. The main crop planted in the structure is millet or sorghum, with okra, rosella and watermelon occasionally being intercropped. The average sorghum production in the 1980s was 400 kg /ha/ year (Van Dijk, 1995). Based on data from Sudan, yields may reach 750 kg/ha in a good year. Quick maturing millet should be planted immediately after the water from a storm has subsided. This crop grows and matures in about 80 days.

8. Experiences with Operation and Maintenance:

The labour demands of Teras use are relatively low, with 6±16 man-days per hectare for construction and 3±18 man-days per hectare for annual maintenance (excluding cultivation). Farmers from the Beja tribe increasingly rent tractors for construction and maintenance purposes, to ensure that the system runs efficiently. Breaches of the bunds will require additional work in order to repair the system. The local dynamics of a drainage system may also require that the conservation structures be continuously adjusted for best performance.

9. Experiences with Monitoring and Evaluation:

Field research has been carried out in the programmes of Water Spreading Research Kassala (WARK; National Council for Research, The Ford Foundation) and Livelihood and Environment (L&E; University of Amsterdam).

When the situation is assessed over the 4 years for which data are available, Teras use tends to show advantages in the form of higher returns in the dryer years than any of the other crop production techniques in the Border Area. ISWC by Teras is therefore likely to be continued because it helps to diversify income sources in normal years, and becomes an outright advantage during dry years. Apparently, the Beja are willing to incur costs in terms of labour opportunities and income lost during wet years, in order to buy the greater overall subsistence security which is vital during dry years.

10. Experiences with related subjects (e.a. erosion prevention, quality of drinking water):

- Erosion prevention: Bunds slow down water flowing overland during and after intense rainfall. Bunds also trap sediment washed away by overland flow. Therefore use of this technology prevents erosion and reduces land degradation.
- Cultural acceptability: There are no cultural restrictions. The Muslim population of Sudan initiated the use of this technology about 50 years ago.

Financial information

11. Experiences with management:

Several rural development programmes were initiated in the region. Earth diversion banks and stone-pitched dams were first built in the Border Area under the Anglo-Egyptian Administration (1898±1956). New SWC techniques were introduced in the region on a larger scale from 1983 onwards.

The merits of ISWC were largely ignored in these projects. Land users applying ISWC have only received modest support from 1988 onwards, for example, in the form of subsidized tractor rent for Teras construction and maintenance.

12. Benefits:

There are no data on costs available, but they are not believed to be high when earthen bunds are constructed manually by a farmer. Mechanical construction methods increase costs.

Socio economic surveys have indicated that application of soil and water conservation practices contributed about an additional 75% to the total household crop production income in the 1980s and 1990s.

Table 1: Developments in livelihood. Changes in total household income shares in livelihood by sector (%) and total teras income shares in crop production and livelihood (%) for Ilat Ayot in the Border Area, 1983 and 1988.

Ilat Ayot (N=58)	1983	1988	% change
% crop production	50	52	+4
% lifestock related	20	6	-70
% labour migration	11	13	+18
% local off-farm	14	25	+79
% networking	5	4	-20
Total livelihood	100	100	
% Teras in crop production (N=26*)	45	49	+9
% Teras in livelihood (N=26*)	19	24	+26

Source: L&E research.

* Based on the sub-group of households using indigenous SWC.

Table 2. Crop production returns. Income per man-hour invested in selected tillage activities (1983 £s) by growing season characteristic and applied technique in four Border Area villages in 1983 and 1988-1990.

Year	Total rainfall and growing season characteristic.	ISWC techniques	Government introduced SWC	Non-SWC techniques
1983	249 mm, normal to dry	57	No data	35
1988	396 mm, wet	70	97	87
1989	218 mm, normal to dry	65	47	74
1990	76 mm, very dry	110	98	82

Source: L&E research (N. 244); Van Dijk (1995: 240, Figure 7.4, adjusted).

Note: ISWC includes and brushwood panels; government-introduced SWC includes earth dams and embankments; non-SWC techniques include valley-bottom and flood-recession cultivation.

General conclusions

13. Generic factors of success and traps ('do's and don'ts'):

The need for spillways must be assessed. The development of spillways may improve the efficiency and reduce maintenance costs. The lack of a spillway can result in breached bunds.

14. What can be used elsewhere, under which conditions:

This technology is appropriate for areas of Sudan where the foothills reinforce high intensity and short duration rainfall, with 150 to 400 mm rainfall, annually. Low infiltration increases the generation of runoff in Teras catchments. Catchments are normally 2 to 3 times the cultivated area in this (semi-) arid region. Teras irrigation suits the lifestyle of the Beja tribe in Sudan, as they are often absent from the land, and this system lends itself to small-scale private enterprise. In West Africa the technology is widely found in valley bottoms.

15. Advantages and disadvantages:

Advantages	Disadvantages
The main advantage of this technique is that simple inexpensive technology is used and it can be constructed by local communities with locally-available materials.	Technique only applicable to increase agricultural yield. No direct benefit to domestic water supply.
The technology is entirely farmer managed and, therefore, not subject to the organizational problems of other soil and water conservation techniques.	Scheme capacity is small, and benefits may not be visible for years.
Costs and labour demands are low	

16. Links to detailed information of this project / technique:

Note: This information may be outdated

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http://www.unep.or.jp/ietc/Publications/TechPublications/TechPub-8a/bunds.asp

ANNEX 9: Fact Sheet

Global overview on artificial recharge

What is artificial recharge?

Artificial recharge is the augmentation of the natural infiltration of water into underground formations (aquifers) by changing the natural conditions. The application of artificial recharge techniques is commonly referred to as Managed Aquifer (MAR). Different MAR techniques have been applied for millennia to manage and store available excess water resources. However, in recent years a wider variety of MAR techniques has become available for a range of applications on different scales, site specific and for different purposes.

Why is MAR becoming important?

Provision of sufficient storage capacity under growing water demand and increasing climate variability is one the main concerns for water managers in the coming decades. Accurate estimates for the required storage capacity do not exist, but it is clear that substantial additional storage capacity will be needed to maintain even minimum supply levels to millions of people both in rural and urban areas. MAR development will be key issue for reaching the MDG for water supply.

Surface water storage in reservoirs behind dams represents the major part of the current installed global storage capacity. However, the recognition of the environmental and social impacts, the growing concerns about dam safety issues and increased sedimentation has clearly demonstrated the limitations of large dams.

Controlled recharge and subsurface storage of water in aquifers, and recovery of this water in times when water is scarce, is an important complementary alternative (to storage behind large dams) for maintaining water supply levels in the future. MAR offers also effective mitigation measures for impacts of overexploitation of groundwater resources such as the intrusion of salt water from the sea into coastal aquifers, land subsidence caused by decreasing groundwater levels and the deterioration of water quality.

MAR can be applied on different scales ranging from large infiltration ponds and recharge dams to community based water harvesting techniques to intercept and store run-off water during rainfall events.

Why this inventory?

In recent years there has been a rapid increase in the use of MAR around the world. Sharing this information will be a strong tool to support and guide the up scaling of successful MAR applications. Publication of knowledge and experiences regarding MAR has progressed, but a sound global overview of applications, and access to information about individual MAR projects is still not available. This inventory of ‘Artificial Recharge of Groundwater in the World’ is launched to provide such a global overview and builds on an earlier initiative of the IAH-MAR commission. The inventory is implemented by IGRAC and the Acacia Institute, in close cooperation with the IAH-MAR Commission and UNESCO-IHP. The aim is to improve the accessibility, dissemination and reuse of information and knowledge related to MAR.

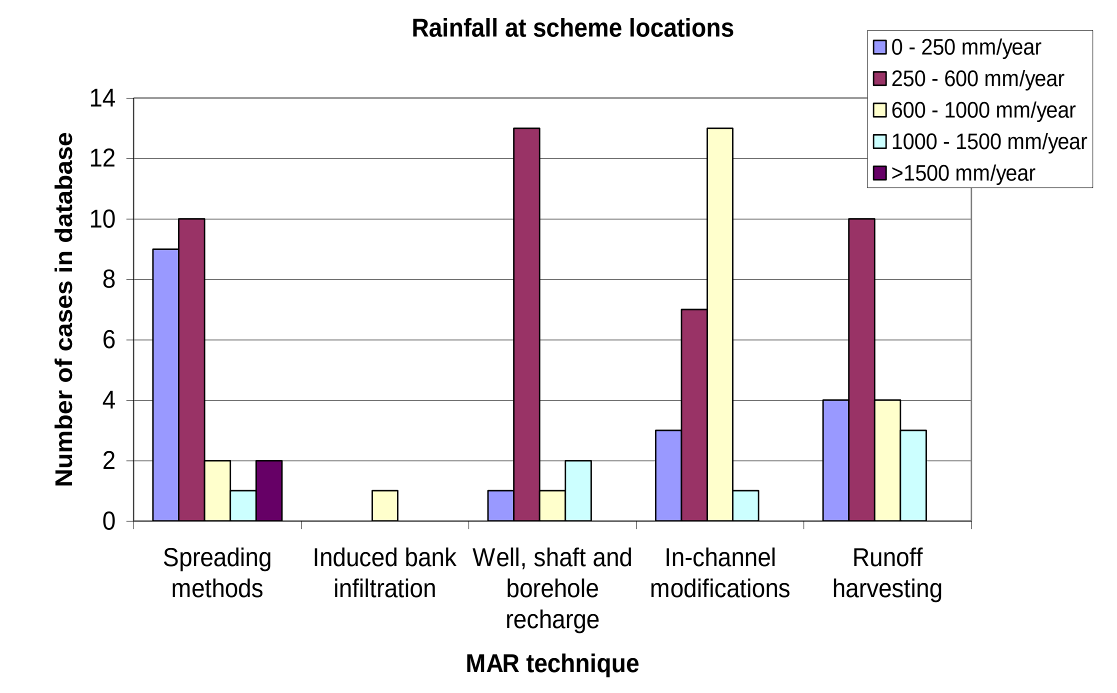
What are the outputs?

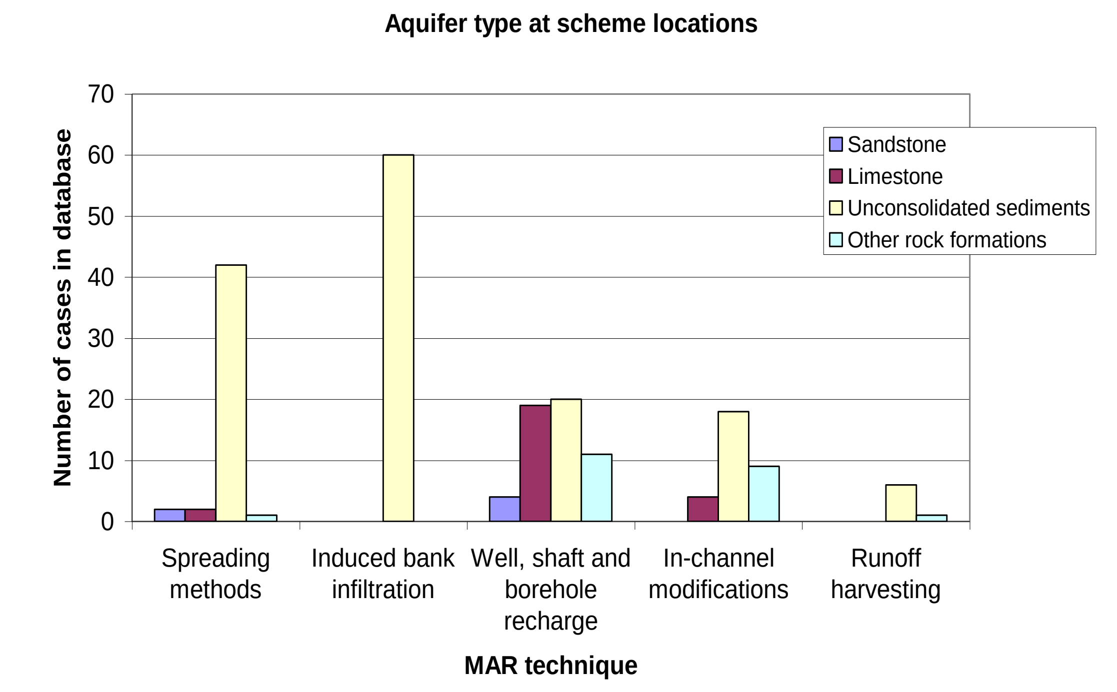
The following outputs are available through the IGRAC website:

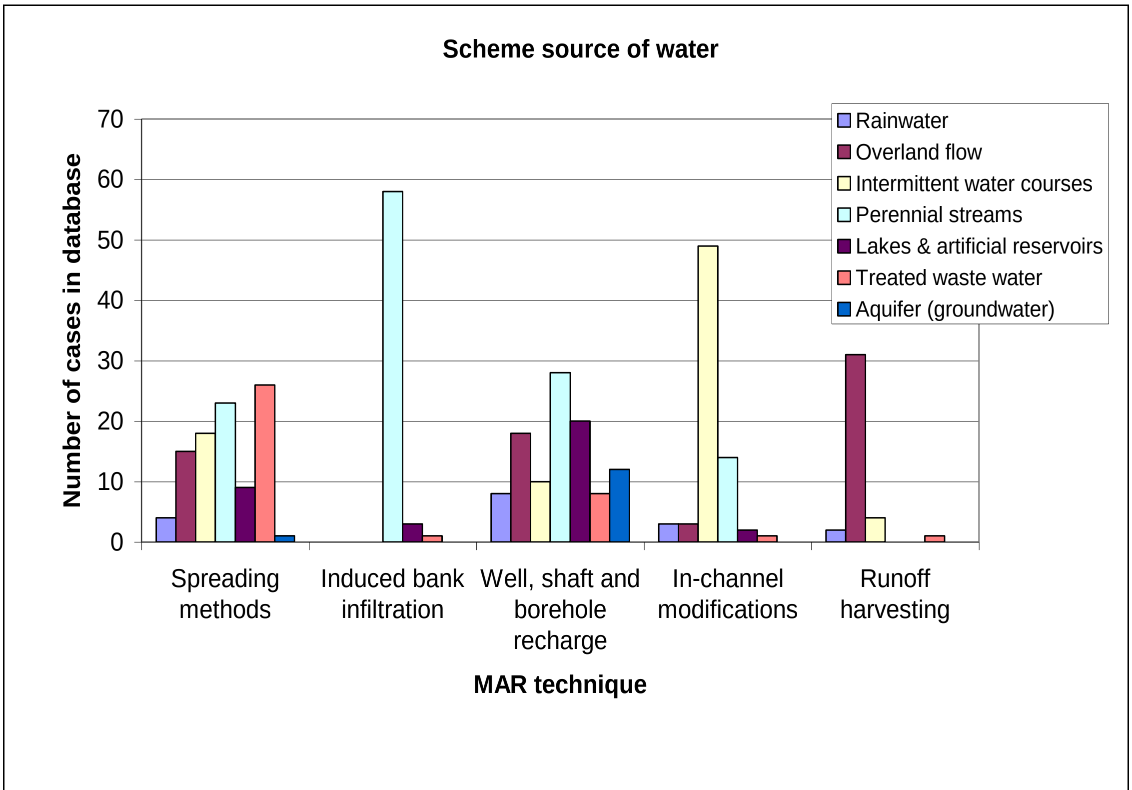
- A classification linked to a description of the 5 main MAR technologies, including 5 case-studies describing an exemplary project in detail for each of the 5 main MAR technologies.
- It is an open active system. The inventory of techniques and parameters is linked to a questionnaire that users are encouraged to fill in and thereby add information to the system.
- A world-wide overview of MAR applications. The user can make a selection from 7 attributes (5 main techniques – see table -, total capacity and total no. of systems). When results are displayed for a selected attribute, a link is provided per country to information available in the so called Meta Information Module (MIM).
- The MIM contains references that were used per country for each of the attributes that can be selected. In addition, the MIM contains information about relevant people, organizations, documents and websites.
- A sophisticated case based reasoning search mechanism providing access to detailed records on individual applications of MAR techniques.

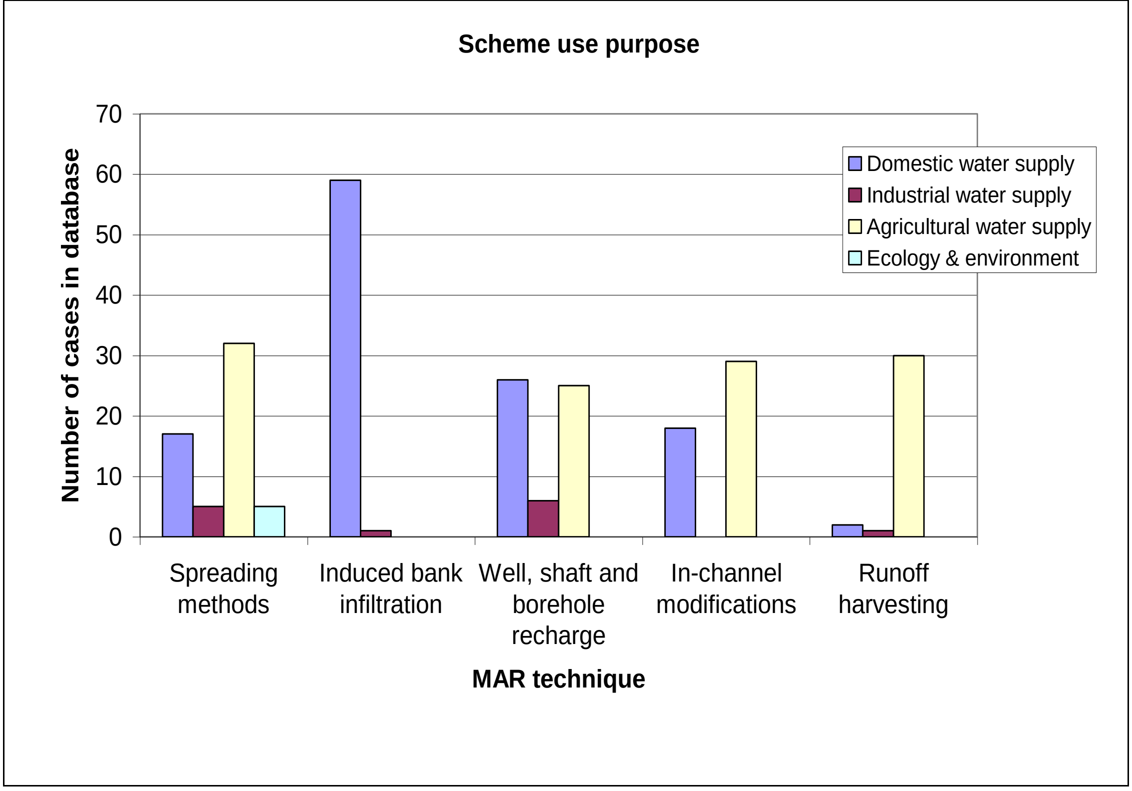
	Technology	Sub type	
Techniques referring primarily to getting water infiltrated	Spreading methods	infiltration ponds & basins	
		flooding	
		ditch, furrow, drains	
		irrigation	
	Induced bank infiltration		
	Well, shaft and borehole recharge	deep well injection	AS(TR)
			ASR
		shallow well/ shaft/ pit infiltration	
Techniques referring primarily to intercepting the water	In-channel modifications	recharge dams	
		sub surface dams	
		sand dams	
		channel spreading	
	Runoff harvesting	barriers and bunds	
		trenches	

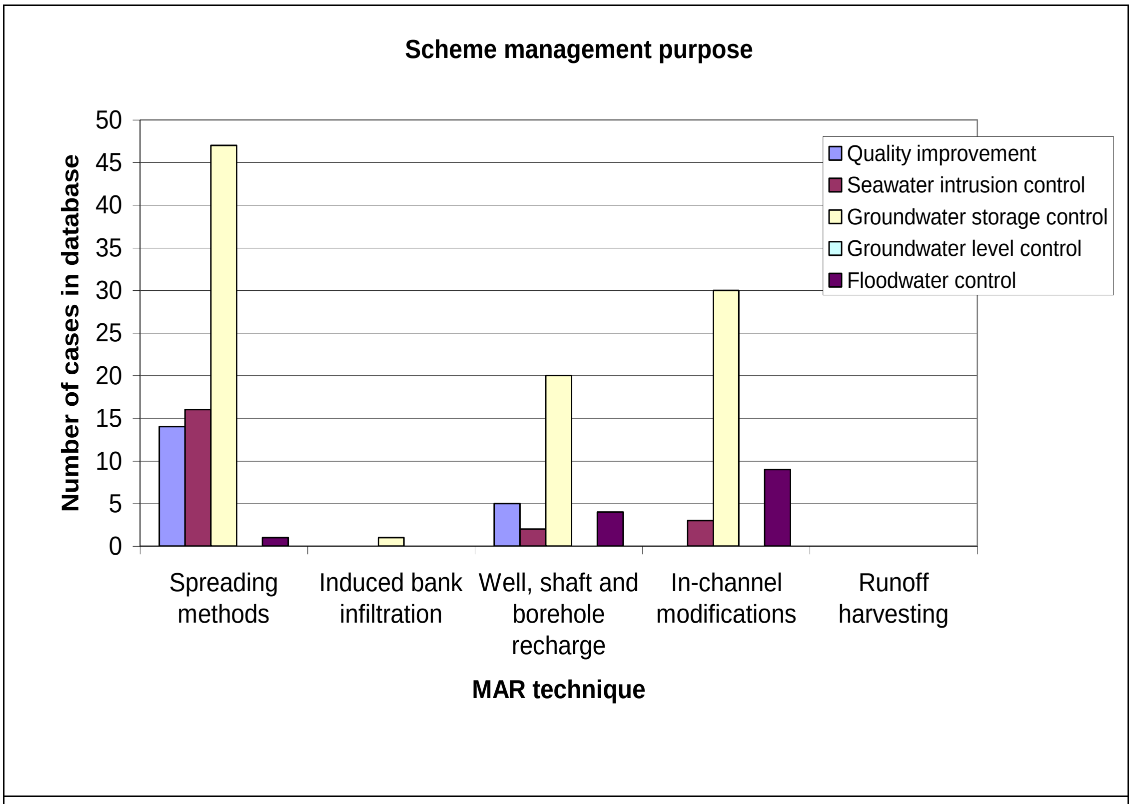
ANNEX 10: Data analyses

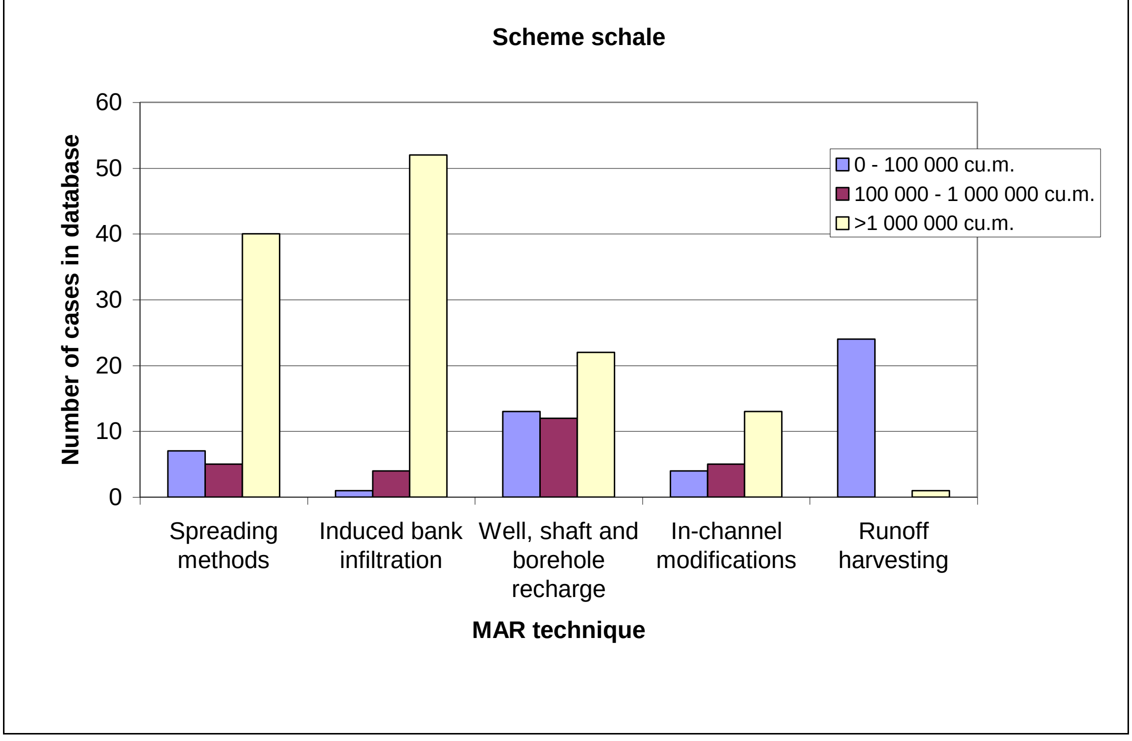


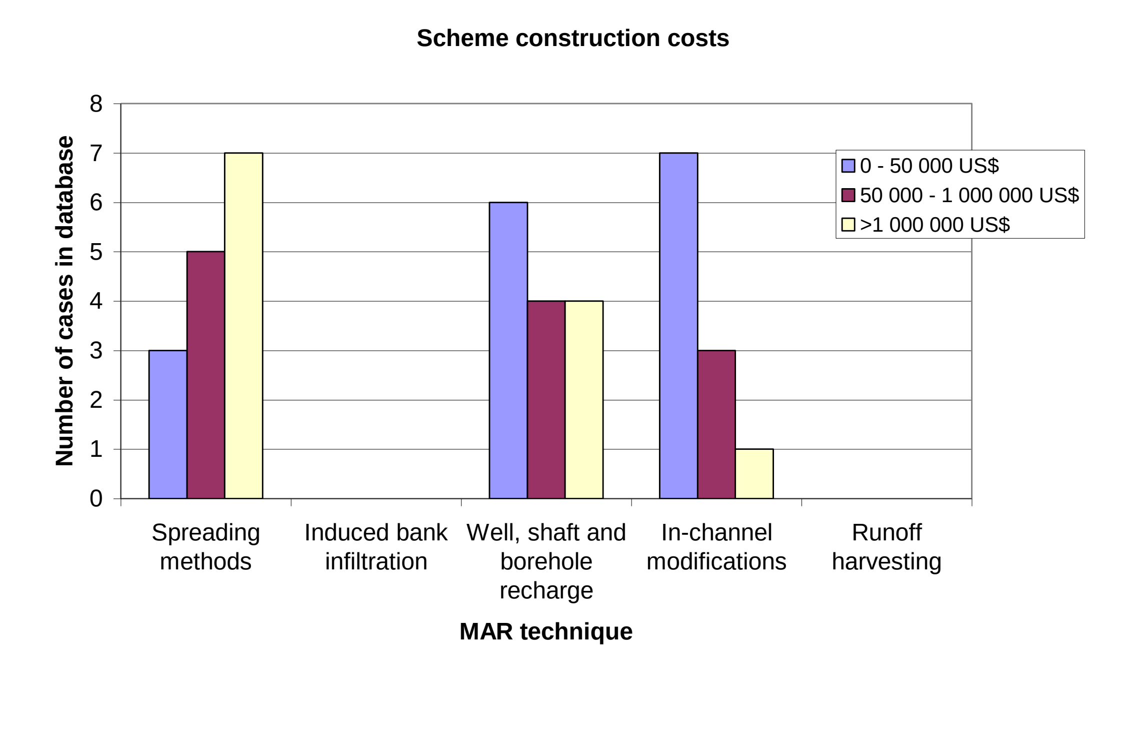



Scheme source of water
Number of cases in database
70
60
50
40
30
20
10
0
Rainwater
Overland flow
Intermittent water courses
Perennial streams
Lakes & artificial reservoirs
Treated waste water
Aquifer (groundwater)
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique

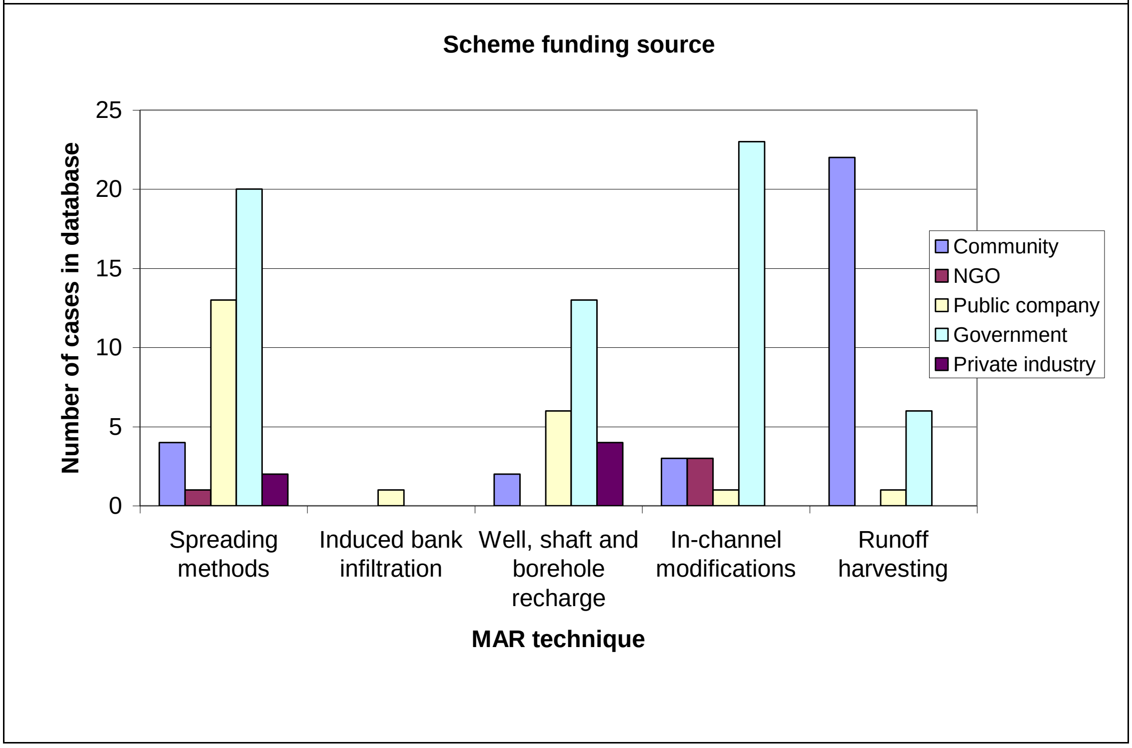

Scheme use purpose
Number of cases in database
70
60
50
40
30
20
10
0
Domestic water supply
Industrial water supply
Agricultural water supply
Ecology & environment
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique


Scheme management purpose
Number of cases in database
50
45
40
35
30
25
20
15
10
5
0
Quality improvement
Seawater intrusion control
Groundwater storage control
Groundwater level control
Floodwater control
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique

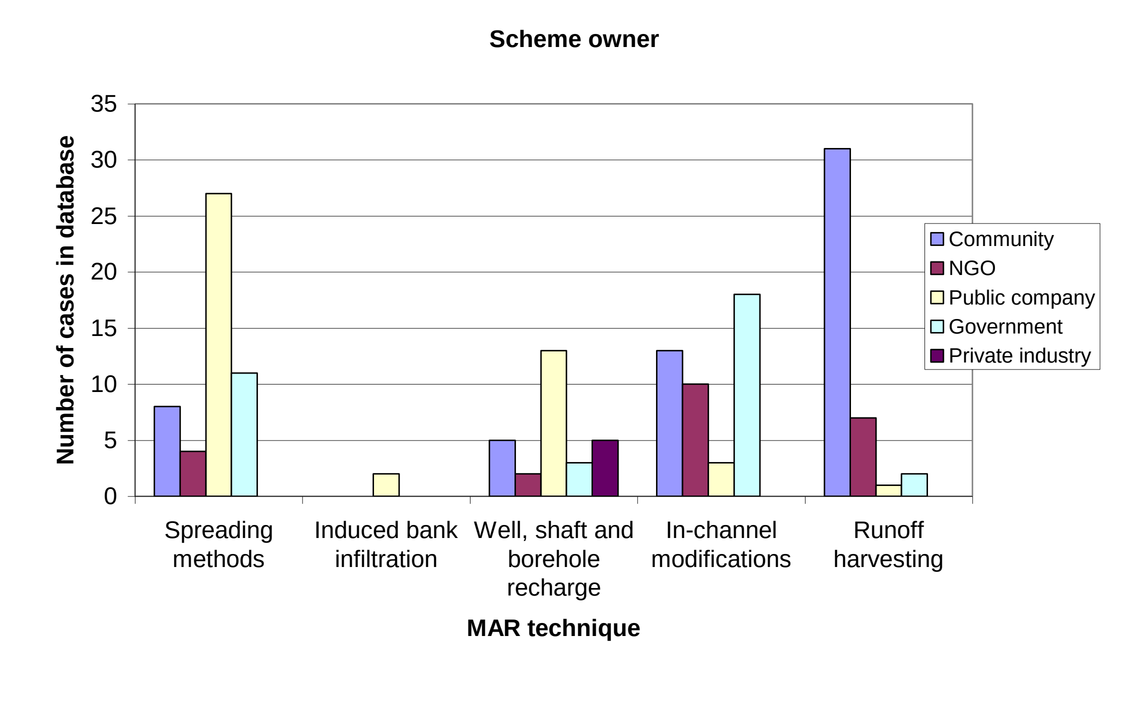

Scheme schale
Number of cases in database
60
50
40
30
20
10
0
0 - 100 000 cu.m.
100 000 - 1 000 000 cu.m.
>1 000 000 cu.m.
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique

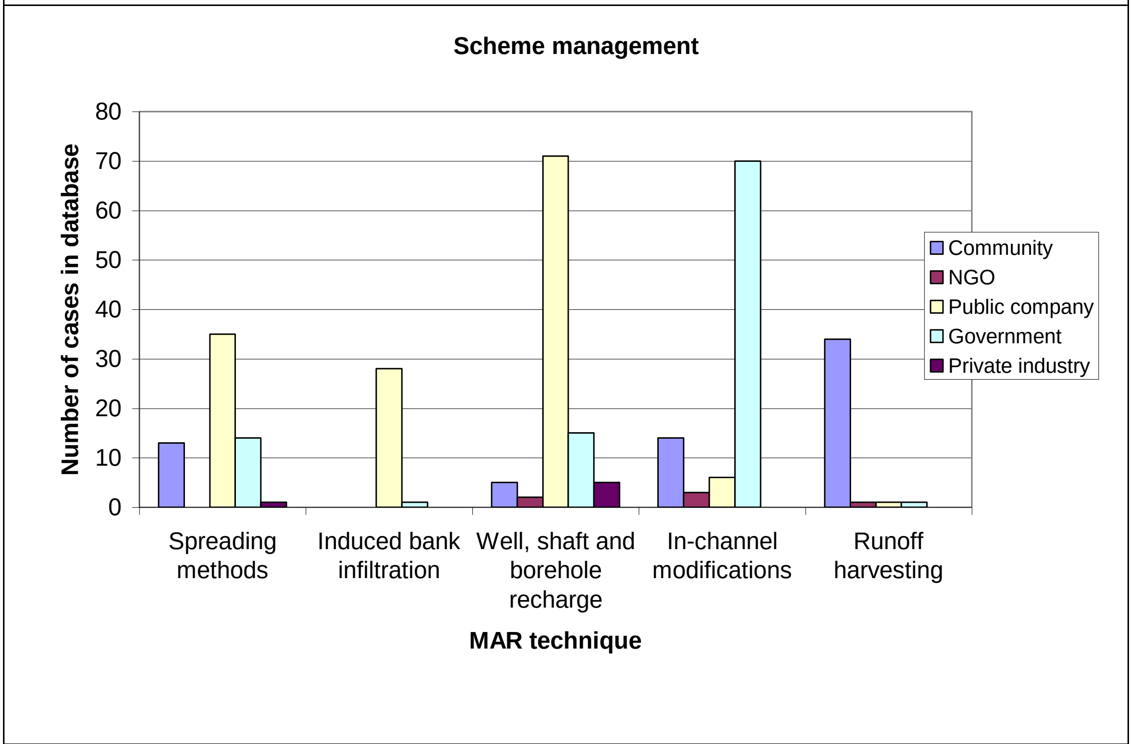


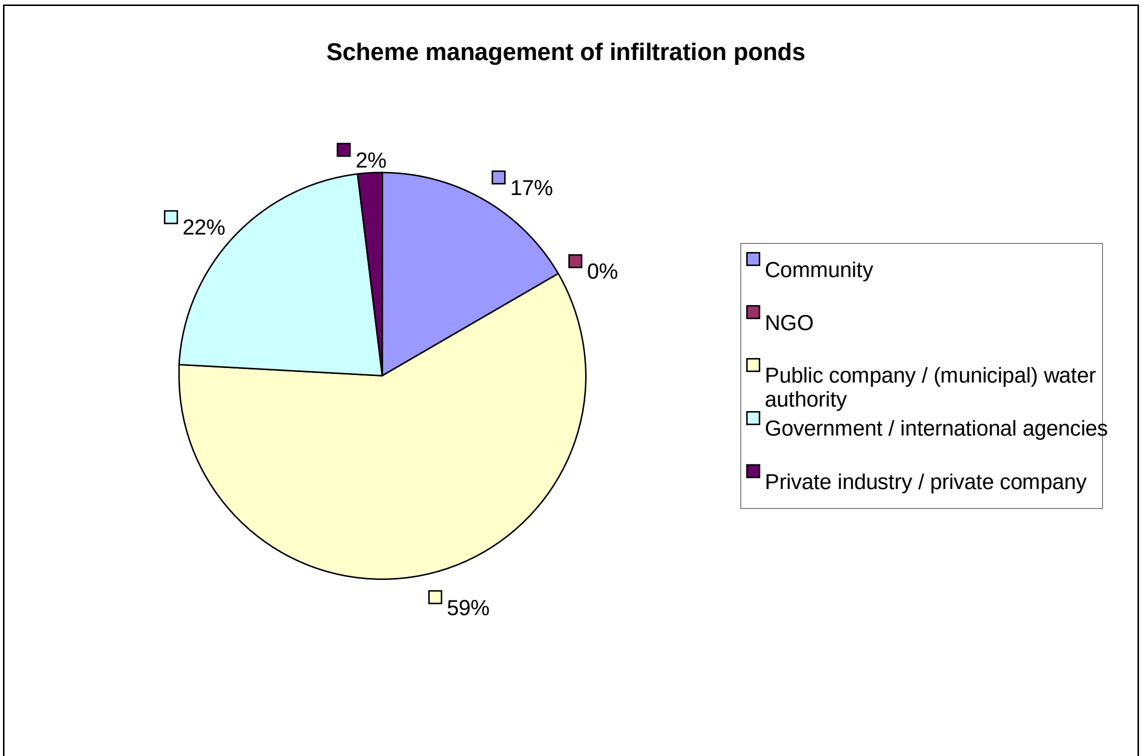
Scheme construction costs
Number of cases in database
0 1 2 3 4 5 6 7 8
0 - 50 000 US$
50 000 - 1 000 000 US$
>1 000 000 US$
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique

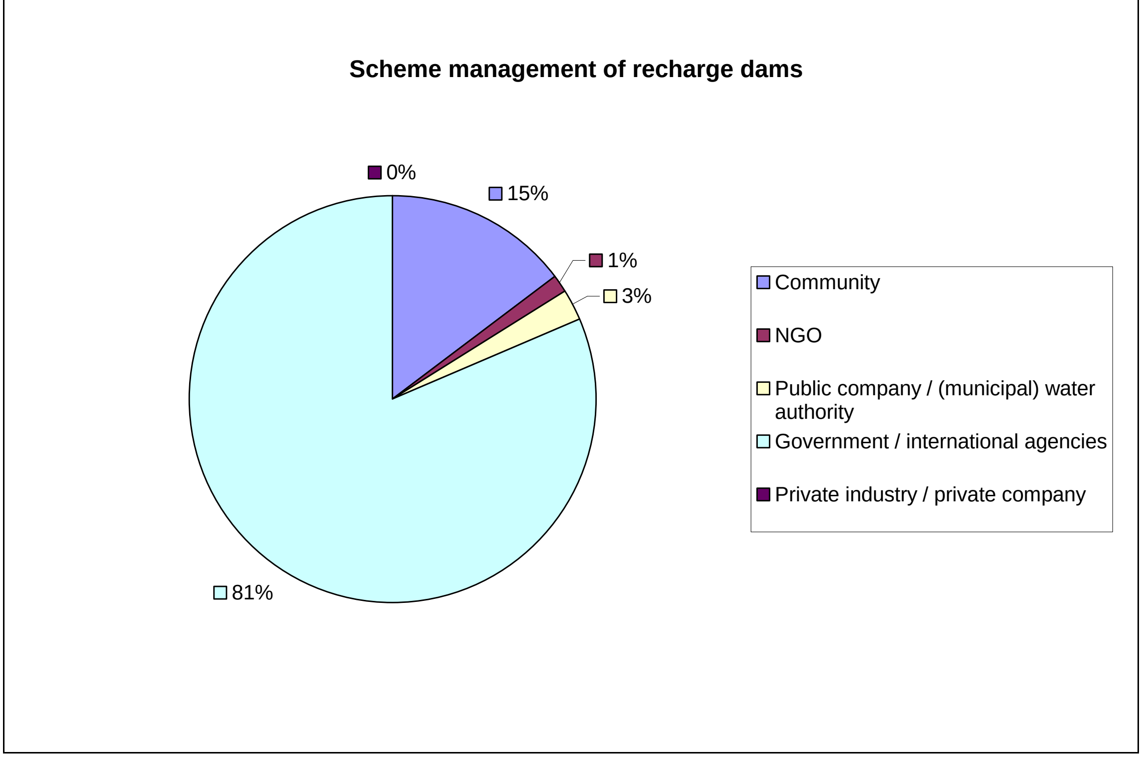


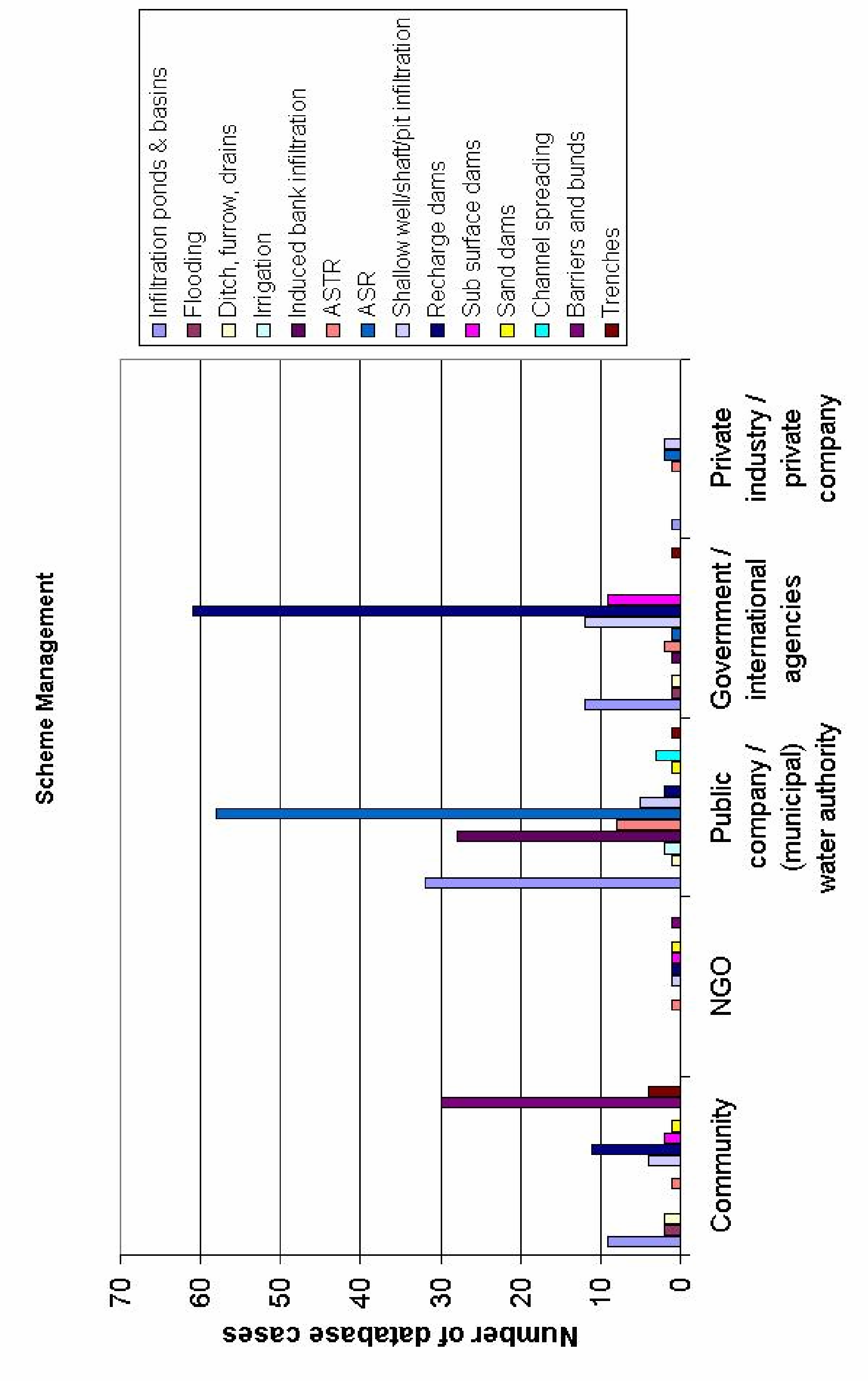
Scheme funding source
Number of cases in database
0 5 10 15 20 25
Community
NGO
Public company
Government
Private industry
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique


Scheme owner
Number of cases in database
35
30
25
20
15
10
5
0
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique
Community
NGO
Public company
Government
Private industry


Scheme management
Number of cases in database
80
70
60
50
40
30
20
10
0
Spreading methods
Induced bank infiltration
Well, shaft and borehole recharge
In-channel modifications
Runoff harvesting
MAR technique
Community
NGO
Public company
Government
Private industry


Scheme management of infiltration ponds
2%
17%
22%
0%
59%
Community
NGO
Public company / (municipal) water authority
Government / international agencies
Private industry / private company


Scheme management of recharge dams
0%
15%
1%
3%
81%
Community
NGO
Public company / (municipal) water authority
Government / international agencies
Private industry / private company


Scheme Management
Number of database cases
0
10
20
30
40
50
60
70
Community
NGO
Public company / (municipal) water authority
Government / international agencies
Private industry / private company
Infiltration ponds & basins
Flooding
Ditch, furrow, drains
Irrigation
Induced bank infiltration
ASTR
ASR
Shallow well/shaft/pit infiltration
Recharge dams
Sub surface dams
Sand dams
Channel spreading
Barriers and bunds
Trenches

Annex 11: Response on questionnaire

IGRAC Global Inventory of Artificial Recharge

Country/ State	USA/California	Name	Adam Hutchinson
		Position	Director of Recharge Operations
E-mail	utchinson@ocwd.c	Date	08/11/2006

	Technique:	A. Techniques referring primarily to the infiltration method								B. Techniques referring primarily to the interception method					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub technique:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well injection		shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:						AS(TR)	ASR							
source	rainwater [1]	p											s		
source	overland flow														
source	intermittent water courses [2]	p											s		
source	perennial streams [2]	p											s		
source	lakes & artificial reservoirs [3]														
source	treated waste water	s							p						
source	aquifer (groundwater) [4]								s						
use	domestic water supply	p							s				s		
use	industrial water supply	p							s				s		
use	agricultural water supply	p							s				s		
use	ecology & environment								p						
managem	quality improvement								p						
managem	seawater intrusion control								p						
managem	groundwater storage control	p							s						
managem	groundwater level control	s							p						
scale	small (scheme capacity < 100 000 m³/year)														
scale	medium (capacity 100 000 - 1 000 000 m³/year)														
scale	large (scheme capacity > 1 000 000 m³/year)	p							s						
geology	unconsolidated sediments	p							s						
geology	sandstone														
geology	limestone														
geology	other rock formations														
	Nr. of schemes														
	(estimated) total capacity (m³/year)	28 million							18 million						

1 Includes rooftop RWH
2 Includes diversion dams
3 Includes storage dams
4 Includes well/ borehole interception

IGRAC Global Inventory of Artificial Recharge

Country/ State	Portugal - Laboratório Nacional
Name	João Paulo Lobo Ferreira e Catarina Diamantino
Position	
E-mail	lferreira@lnec.pt
	cdiamantino@lnec.pt
Date	Nov. 15, 2006

		A. Techniques referring primarily to the infiltration method								B. Techniques referring primarily to the interception method					
	Technique:	**Spreading methods**				**Induced bank infiltration**	**Well, shaft and borehole recharge**			**In-channel modifications**				**Runoff harvesting**	
	Sub technique:	**infiltration ponds & basins**	**flooding**	**ditch, furrow, drains**	**irrigation**		**deep well injection**		**shallow well/ shaft/ pit infiltration**	**recharge dams**	**sub surface dams**	**sand dams**	**channel spreading**	**barriers and bunds**	**trenches**
	Attribute:						**AS(TR)**	**ASR**							
source	rainwater [1]														
	overland flow														
	intermittent water courses [2]												p		
	perennial streams [2]														
	lakes & artificial reservoirs [3]														
	treated waste water														
	aquifer (groundwater) [4]	p							p						
use	domestic water supply														
	industrial water supply														
	agricultural water supply	p							p						
	ecology & environment												p		
managem	quality improvement	p							p				p		
	seawater intrusion control														
	groundwater storage control														
	groundwater level control	s							s				s		
scale	small (scheme capacity < 100 000 m³/year)	p							p				p		
	medium (capacity 100 000 - 1 000 000 m³/year)														
	large (scheme capacity > 1 000 000 m³/year)														
geology	unconsolidated sediments	p							p				p		
	sandstone														
	limestone														
	other rock formations														
Nr. of schemes		3							1				2		
(estimated) total capacity (m³/year)															

1 Includes rooftop RWH; 2 Includes diversion dams; 3 Includes storage dams; 4 Includes well/ borehole interception

IGRAC Global Inventory of Artificial Recharge

Country/ State	Northern Territory / Australia	Name	Peter Jolly	E-mail	peter.jolly@nt.gov.au
		Position	Principal Engineer Water Resources	Date	23/11/2006

	Technique:	*A. Techniques referring primarily to the infiltration method*								*B. Techniques referring primarily to the interception method*					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub technique:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well injection		shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:						AS(TR)	ASR							
source	rainwater [1]														
source	overland flow														
source	intermittent water courses [2]														
source	perennial streams [2]														
source	lakes & artificial reservoirs [3]														
source	treated waste water	p													
source	aquifer (groundwater) [4]							p							
use	domestic water supply							p							
use	industrial water supply														
use	agricultural water supply	p													
use	ecology & environment														
managem	quality improvement	s						s							
managem	seawater intrusion control														
managem	groundwater storage control	p						p							
managem	groundwater level control														
scale	small (scheme capacity < 100 000 m³/year)							p							
scale	medium (capacity 100 000 - 1 000 000 m³/year)	p													
scale	large (scheme capacity > 1 000 000 m³/year)														
geology	unconsolidated sediments	p													
geology	sandstone							p							
geology	limestone														
geology	other rock formations														
Nr. of schemes		2						1							
(estimated) total capacity (m³/year)		800,000*						40.000							

1 Includes rooftop RWH
2 Includes diversion dams
3 Includes storage dams
4 Includes well/ borehole interception

IGRAC Global Inventory of Artificial Recharge

Country/ State	Serbia
Name	Borivoje Mijatović
Position	President od IAH National Chapter
E-mail	borismij@eunet.yu
Date	27/11/2006

	Technique:	A. Techniques referring primarily to the infiltration method								B. Techniques referring primarily to the interception method					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub technique:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well AS(TR)	injection ASR	shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:														
source	rainwater [1]	s													
source	overland flow														
source	intermittent water courses [2]														
source	perennial streams [2]	p						p							
source	lakes & artificial reservoirs [3]														
source	treated waste water														
source	aquifer (groundwater) [4]														
use	domestic water supply	p						p							
use	industrial water supply	s						s							
use	agricultural water supply														
use	ecology & environment														
managem	quality improvement	p						p							
managem	seawater intrusion control														
managem	groundwater storage control	s						s							
managem	groundwater level control														
scale	small (scheme capacity < 100 000 m³/year)														
scale	medium (capacity 100 000 - 1 000 000 m³/year)														
scale	large (scheme capacity > 1 000 000 m³/year)	p						p							
geology	unconsolidated sediments	p													
geology	sandstone														
geology	limestone							p							
geology	other rock formations														
	Nr. of schemes	1						1							
	(estimated) total capacity (m³/year)	19000000						3000000							

1 Includes rooftop RWH
2 Includes diversion dams
3 Includes storage dams
4 Includes well/ borehole interception

	Country/ State	China			Position	chang'an unniverisity in xi'an						E-mail	xm1-1@163.com		
												Date			

	Technique:	A. Techniques referring primarily to the infiltration method								B. Techniques referring primarily to the interception method					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub technique:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well injection		shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:						AS(TR)	ASR							
source	rainwater [1]			p											
	overland flow			s	p										
	intermittent water courses [2]														
	perennial streams [2]				p										
	lakes & artificial reservoirs [3]														
	treated waste water														
	aquifer (groundwater) [4]														
use	domestic water supply														
	industrial water supply			s	s										
	agricultural water supply		p	p	p										
	ecology & environment		s												
managem	quality improvement														
	seawater intrusion control														
	groundwater storage control			p	p										
	groundwater level control														
scale	small (scheme capacity < 100 000 m³/year)		s												
	medium (capacity 100 000 - 1 000 000 m³/year)														
	large (scheme capacity > 1 000 000 m³/year)				p										
geology	unconsolidated sediments														
	sandstone														
	limestone														
	other rock formations	p		p											
Nr. of schemes															
(estimated) total capacity (m³/year)															
1	Includes rooftop RWH	2	Includes diversion dams			3	Includes storage dams			4	Includes well/ borehole interception				

IGRAC Global Inventory of Artificial Recharge

Country/ State	Spain
Name	IGME
Position	
E-mail	
Date	

	Technique:	A. Techniques referring primarily to the infiltration method								B. Techniques referring primarily to the interception method					
		Spreading methods				Induced bank infiltration	Well, shaft and borehole recharge			In-channel modifications				Runoff harvesting	
	Sub technique:	infiltration ponds & basins	flooding	ditch, furrow, drains	irrigation		deep well injection		shallow well/ shaft/ pit infiltration	recharge dams	sub surface dams	sand dams	channel spreading	barriers and bunds	trenches
	Attribute:						AS(TR)	ASR							
source	rainwater [1]														
source	overland flow														
source	intermittent water courses [2]							s	p						
source	perennial streams [2]	p													
source	lakes & artificial reservoirs [3]														
source	treated waste water														
source	aquifer (groundwater) [4]							p							
use	domestic water supply	p						p							
use	industrial water supply														
use	agricultural water supply								p						
use	ecology & environment														
managem	quality improvement														
managem	seawater intrusion control														
managem	groundwater storage control	p						p							
managem	groundwater level control														
scale	small (scheme capacity < 100 000 m³/year)														
scale	medium (capacity 100 000 - 1 000 000 m³/year)							p	p						
scale	large (scheme capacity > 1 000 000 m³/year)	p													
geology	unconsolidated sediments	p							p						
geology	sandstone														
geology	limestone							p							
geology	other rock formations														
	Nr. of schemes							1	2						
	(estimated) total capacity (m³/year)	4,00E+06						1,00E+06	1,50E+05						

1 Includes rooftop RWH
2 Includes diversion dams
3 Includes storage dams
4 Includes well/ borehole interception